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FACTORS INFLUENCING WATER AND PARTICLE MOVEMENT INTO DRAINS

Five Independent Studies of Drain Clogging Conducted as Part of Western Regional Research Project W-51

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FACTORS INFLUENCING WATER AND PARTICLE MOVEMENT INTO DRAINS

Five Independent Studies of Drain Clogging Conducted as Part of Western Regional Research Project W-51

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ABSTRACT

Clogging of drain openings by soil particle movement reduces the efficiency of agricultural subsurface drains. A multifaceted study relative to drain clogging problems showed some of the causes of clogging. Fine sand and silt can migrate and clog drain joints and openings. Periodic reducing conditions in the soil cause dissolution of iron, which is precipitated as a viscous plugging gel in the oxidizing environment of the drain opening.

Movement of soil particles within the envelope itself can cause a reduction in drain envelope permeability by reducing the size of large pores. Coarse single-size envelopes, such as pea gravel, are not effective for preventing movement of fine particles into drains. Most material finer than a No. 60 screen (0.25 mm), should be excluded from granular drain envelopes. For graded granular envelopes, drain openings should be larger than most of the envelope particles. Envelope material will bridge over drain openings if the particles are larger than one-third the diameter of a circular opening. A slot has the same effective size as a circular hole with a diameter three times the narrow dimension of the slot. Drain envelopes that restrain the soil without acting as a filter will maintain the efficiency of subsurface drainage.

KEYWORDS: Drainage, filter, drain envelope, ochre, tile drainage, subsurface drains, synthetic envelope, drain clogging, sedimentation.

PREFACE

Unsatisfactory performance of closed subsurface drains is often the result of water and particle movement near the drains. Little is known about the behavior of the water and soil particles in this critical portion of a drainage system. Water travels through the cross-section of relatively large flow between drains, and then must converge to pass through the relatively small drain openings. Upon convergence, gradients and flow velocities increase and soil particles undergo stresses not existing in other parts of the flow system. The high flow velocities and related forces on the skeleton of the soil structure sometimes allow particles to move where they clog drain openings. A new equilibrium may then be established by the decreased capacity of the drain to remove water from the soil.

Restricted water entry into drains has been such a significant problem in many locations that research on the matter was included in Western Regional Research Project W-51.

From 1966 to 1974, research was conducted in the laboratory and field on various phases of the problem. When the Regional Project was terminated, the unpublished research results were collected for this report. One phase of the work reported deals with determining the characteristics of particles that clog the joints of field drains. Another aspect was directed toward understanding the mechanism of particle movement. Full-scale laboratory experiments were conducted to develop design criteria for drain envelopes. Work included both natural and artificial envelope materials. Additional laboratory tests were made of envelope materials to improve understanding of their functions.

Although it did not result in engineering specifications for an ideal drain envelope, the research reported upon here provides a strong fundamental base for future research.

L. S. Willardson
Compiler

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PARTICLE SIZE, STRUCTURE, AND MINERALOGY OF CLOGGED DRAIN OPENINGS

By Frederick F. Peterson[1]

INTRODUCTION

The research reported here was initiated to determine the materials causing extensive tile joint-clogging in the Coachella Valley, Calif. Several joint-clogging materials have been hypothesized. Calcium carbonate (travertine) deposits fill and block some tile lines, though such obstruction does not seem widespread. Iron and manganese hydrous oxide deposits, such as those plugging drain openings in the Imperial Valley, Calif., have not been considered a serious problem, though deposits have been found in some joints of Coachella Valley drains. A third and popular hypothesis was that of plugging by infiltration and lodgment of progressively smaller sand grains.

Inflows of sand into tile lines have been observed during backfilling and water compaction. Sand has been found in the joints of drains which failed even though their interior bores were open. Additional circumstantial evidence for sand plugging was low-clay, very fine sandy, and fine sandy soils (which are unstable when saturated), and similar fine-texture materials in the coarse sand filter material commonly used on these tile lines.

The hypothesis of sand infiltration-plugging has been particularly difficult to investigate because plugged tile lines have to be opened in a pit dug into unstable soil below the water table. Any purely mechanical bridging and fitting of sand grains as a dense pack in the joint would be destroyed when the joint was separated for inspection. Therefore, it was apparent that some technique was needed for direct inspection of the materials in undisturbed and plugged joints, along with petrographic thin-section techniques for studying soil fabrics.

Microscopic examination of plugged tile joints, undisturbed except for impregnation with plastic, allows identification of the individual sand and silt grains involved in plugging. By comparing these thin sections and their packing patterns (fabrics) with the filter or envelope material and surrounding soil materials, one can directly determine whether particles have been deposited and can identify particles which are plugging the joints.

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[1]Formerly Assistant Professor, Soils and Plant Nutrition Department, University of California, Riverside; presently Professor, Plant Soil Water Science Division, University of Nevada, Reno.

METHODS OF INVESTIGATION

Obtaining Plugged Tile Joints in Undisturbed State

Two five-inch-I.D. tongue-and-groove concrete drain lines that were functioning poorly in a Mecca very fine sandy loam[2] were exposed in 20- by 20-foot pits dug to within 6 inches of the tiles. The pits were then deepened a foot on each side of the tile lines, leaving the lines supported by and encased in soil and filter or envelope material. Since the water tables were well above both lines at the time of the excavations, mud and water had to be continually removed from the pits. The supporting soil stood rigidly, causing only an insignificant (2-3 mm) displacement of the joints.

The joints were located by scraping off a bit of the top envelope material. A small tunnel was dug under the joint, through the soil ridge supporting the line. The joint was wrapped with gauze bandage, and then with plastic tape. Though most of the envelope material unavoidably fell off the tile sides and bottoms, small portions were preserved under the bandage.

The tiles on each side of the wrapped joint were held in place by embedding them in quick-setting plaster of paris. The plaster was poured into a wooden cradle which had been slung under the tiles with U-bolts. When the plaster base was set and rigid, the U-bolts were tightened to secure the tiles, the tile line was broken open at an adjacent joint, and the two tiles, in their plaster bed with an undisturbed joint, were hoisted out of the pit.[3] The tiles were wrapped in plastic and transported to the soil physics laboratory of the University of California in Riverside on the presumption that if they remained moist, water films would hold any plugging sand grains in place.

The two sets of immobilized tiles, and their joints, are referred to as joint 1 and joint 2.

Plastic Impregnation and Sectioning of Joints

The tiles were thoroughly air dried in the sun. Then the joints were impregnated with a mixture of 40 percent "Laminac 4116" polyester resin and 60 percent styrene, catalyzed with 8 drops of 60 percent methylethylketone peroxide ("Lupersol DDM") catalyst per 100 g of mixture. By experimenting, we found that this mixture would "wick" well in the gauze, soak into fine cracks, and harden in a few hours. Coarse pores needed to be filled with a more viscous solution of plastic applied from the inside.

A 4-inch-long section that included the plastic-impregnated joint was sawed out of the pipe with a saw of 12-inch-diameter industrial diamond while the tiles were still in the cradle. Once the joint section was freed, it was

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[2] Sample sites are on the Rutherford Ranch, southwest corner of intersection of Van Buren Street and Avenue 53, Coachella Valley, Calif.

[3] The cradle-and-plaster-bed device was engineered by S. J. Richards and J. R. Spencer. Without the skill, equipment, and aid of the Coachella Valley County Water District, samples could not have been obtained.

sawed axially into quadrants with a petrographic diamond saw (which cuts a 2.3 -mm slash). These quadrants were further sectioned into segments about 4.5 mm thick at their inner edge (that is, the inside surface of the tile). These sections thus displayed cross-sections of the tongue-and-groove tile joints thin enough to see through yet thick enough to see the three-dimensional arrangement of sand grains entrapped in the plastic. Both standard sections 20-30 μm thick and sections 70-100 μm thick were ground from selected sections for petrographic and binocular microscopic examination.[4]

Filter Envelope and Soil Characterizations

The filter envelope and soil materials surrounding the plugged joints required parallel study to determine the source of the joint-plugging deposits seen in petrographic sections. Tables 1 and 2 show the particle-size distribution and qualitative mineralogical composition determined for those materials.

Sample 709 was a relatively fine-textured (very fine sandy loam) stratum. It was taken from the Oasis gravel pit, where most of the envelope material for the Coachella Valley was obtained. This finely bedded deposit, found at the Oasis pit, is representative of the polluting fines which are mixed into the bulk filter envelope material from the pit and might migrate to plug tile joints.

Sample 710 is a fine gravel and very coarse and coarse sand stratum from the Oasis pit. The sample represents most of the material used for filter envelopes.

Sample 711 is iron-oxide-stained brownish-yellow filter envelope material from immediately on top of tile joint 1, that is, from within 2-3 inches of the joint.

Sample 712 is a very fine sandy grayish loam from 30 inches deep in the Mecca soil at the site of tile joint 1. It is calcareous, and the gray colors indicate gleying, that is, reduction and solublization of free iron oxides.

Sample 713 is a relatively brownish (5Y4/2, moist)[5] very fine sandy loam from the upper zone (20-inch depth) in the Mecca soil at the site of tile joint 2, calcareous, with a few fine distinct brownish-yellow mottles. Mottles indicate periodic reducing and oxidizing conditions that cause segregation of free iron oxides.

Sample 714 is a relatively grayish (5GY5/1, moist) fine sandy loam from the lower or substratum zone (52-inch depth) in the Mecca soil at the site of tile joint 2; not mottled, weakly calcareous due to a few shells, and the gray colors indicate gleying.

Clods of samples 709, 710, 713, and disturbed slaked material from samples 711, 712, and 714 were impregnated with plastic. They were then sectioned and

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[4]Yuki Aochi prepared the thin sections and performed the mineralogical and particle size-distribution determinations.

[5]Color coding from the Munsell Book of Color. Munsell Color Division, Kollmorgen Corp., Baltimore, Md. 6 p. plus 1,150 color standards. 1973.

ground to thin sections for petrographic microscopic study of their particle arrangements or fabrics.

Artificial Tile-Joint Plugging

In order to develop a technique for field use in impregnating, sectioning, and recognizing joint-plugging materials, several artificially filled butt joints were prepared. The plugging material was brushed onto the joints, which were then bolted together, wetted with drops of water, dried several times, bandaged, plastic-impregnated, and sectioned. The artificial plugging materials used were:

1. A water slurry of silt and clay-free fine and very fine sand from the Oasis pit.

2. Oasis pit fine sand mixed with freshly precipitated viscous ferric hydroxide.

3. Oasis pit fine sand mixed with equal parts of freshly precipitated viscous ferric and manganese hydroxides.

The tests included a tongue-and-groove concrete tile joint artificially plugged with particles moving in drainage water.[6]

OBSERVATIONS AT SAMPLE SITES

The two 5-inch tongue-and-groove concrete tile lines dug up for sampling contained Mecca very fine sandy loam. Both lines were flowing at much reduced rates and were more than a foot below the water table. The field was poorly drained. Slumping of the unstable Mecca soil into the sampling excavations was pronounced.

The Mecca soil at the sampling site is a coarse-loamy mixed (calcareous) hyperthermic Typic Torriothent.[7] The mineralogical denotation of the soil family name is somewhat misleading for our purposes since the Mecca soils have only a very small content of calcium carbonate but are prominently micaceous. They contain significantly large amounts of very fine and fine sand but only small portions of fine silt and clay; hence, their exceeding mechanical instability when saturated.

Drab olive-gray subsoil colors below 30 inches of depth indicate a continuous reducing environment, whereas a somewhat higher matrix chroma and a few fine distinct yellowish-brown mottles at about 30 inches indicate that condi-

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[6]This artificially plugged joint was prepared in the laboratory by S. J. Richards using an Oasis gravel envelope dirtied with Mecca-like soils material.

[7]The old Mecca soil series is "not classified because of original broad or vague definition" in the 1973 U.S. Soil Taxonomy; the soil at the sampling sites is a coarse-loamy mixed (calcareous) hyperthermic Typic Torriothent and might now be identified with the Aco series.

TABLE 1.--*Particle-size distribution of filter envelope materials and Mecca soil materials*[1]

Sample number and names	Very coarse sand (1-2 mm)	Coarse sand (0.5-1 mm)	Medium sand (0.25-0.5 mm)	Fine sand (1-0.5 mm)	Very fine sand (0.05-0.1 mm)	Coarse silt (20-50 μ)	Medium silt (5-20 μ)	Fine silt (2-5 μ)	Total silt (2-50 μ)	Clay <2μ	Textural class
	Percent										
709: Oasis pit finer strata	6	3	2	10	50	21	4	1	26	3	vfsl
710: Oasis pit coarser strata	43	46	10	(2)	(2)	0	(2)	(2)	(2)	1	co s
711: Fe-stained filter sand (No. 1)[3]	55	13	18	6	3	2	1	(2)	3	2	co s
712: Mecca soil at 30" (No. 1)	(2)	(2)	4	30	56	6	1	(2)	7	3	vfs
713: Mecca soil at 20" (No. 2)	(2)	(2)	3	16	39	18	11	4	33	9	vfsl
714: Mecca soil at 52" (No. 2)	(2)	(2)	10	45	35	7	1	(2)	8	2	fs

[1]Dispersion with Na-hexametaphosphate and overnight shaking; clay and finer silts by pipette; sands by sieving for more than 10 min on 3-way bumping shaker.
[2]Trace.
[3]Parenthetical number indicates tile joint 1 or 2.

TABLE 2.—*Qualitative mineralogical composition of gravel filter envelope materials and Mecca soil materials of the Coachella Valley as determined by simple X-ray diffraction techniques*[1]

Sample No. and name	Size fraction	Qualitative mineralogical composition[2]
709: Oasis pit finer strata	<2 μ	Mt>>B = K
	2-5 μ	B>V = Mt = K
(Medium silt)	5-20 μ	B = V>>>>K; traces Mt, CA, Q, F
(Coarse silt)	20-50 μ	B = V>>>K; Q>>F>>H = Ca
(Very fine sand)	50-100 μ	B>>>V>K; Q>F>>>H
(Fine sand)	100-250 μ	B>>>>>V>>>K; Q(?), F, H, Ca, D(?)
(Medium sand)	250-500 μ	B>>>>>V; no other peaks clearly present
710: Oasis pit coarser strata	<2 μ	V>Mt = B = K
	2-5 μ	V>>>B = K>Mt
711: Fe-stained filter sand	<2 μ	Mt>>>>K>B
	2-5 μ	Mt>>>>K = V>B
712: Mecca soil C1, 30"	<2 μ	Mt>>>K = V>B
	2-5 μ	Mt = V = B = K
713: Mecca soil C1, 20"	<2 μ	Mt>>V = B = K
	2-5 μ	V = B = K>Mt
	5-20 μ	B>V>K; Ca>>>Q>F
	20-50 μ	B>V>K; Q>>F, A
	50-100 μ	B>>V>K; Q>F
	100-250 μ	B>>>V>>K; Q>>F
	250-500 μ	F>Q; traces B
714: Mecca soil C2, 52"	<2 μ	Mt>>B = K = V
	2-5 μ	V = V>Mt
	5-20 μ	V = B>>>K; F, Q(?), D(?)
	20-50 μ	B = V>>K; Q>F; H, Ca
	50-100 μ	B>>V>K; F = Q, trace A
	100-250 μ	B; dominantly Q = F
	250-500 μ	F > Q; trace B

[1]Soil material size separated by centrifugation and sieving after dispersion by NaCl-saturation and shaking; mineral fractions given saturation treatments with N $MgCl_2$, $MgCl_2$ and 10 percent glycerol; KCl and the K-saturated samples were in part heated to 200° and 500°C before examination.

[2]Notation:

Mt: montmorillonite	Q: quartz
V: vermiculite	F: feldspars, mainly plagioclase
B: biotite	Ca: calcite
Hb: hydrobiotite	D: dolomite
K: kaolinite	H: hornblend

=: represents equal diffraction peak heights

>, >>, >>>: represents 1x, 2x, 3x greater X-ray diffraction peak height than the next mineral listed.

tions in the soil are alternately reducing and oxidizing. Reducing conditions would convert ferric oxide to soluble ferrous compounds and provide a source of soluble iron which could be precipitated in an oxidized soil zone around the joint of an air-filled drainage tile.

When tile joint 1 was exposed, prominent brownish-yellow (10YR6/6M) bands of free iron oxide stained the Oasis pit filter sand several inches wide at each joint in the line. The iron staining extended through the joints to inside the tile; this morphological pattern suggests diffusion of oxygen out through the joint into the reduced subsoil, with resultant oxidation and precipitation of iron. Water dribbled from inside the pipe, dribbled when joint 1 was bared, and flowed from only one side of the line when it was opened. Presumably, the line was not full, so oxygenated air was in the line at this point. The bared ends of the adjacent tiles showed infiltrated sand weakly cemented by prominent brownish-yellow iron oxide and black manganese oxide coating. The iron coating was most prominent around the upper two-thirds of the joint, whereas the black manganese oxide occurred primarily around the lower third and on the inside bottom of the tile. Micaceous very fine sand, 0-2 mm thick, irregularly stained by manganese oxide, was found inside the tile. Thin-section studies indicate iron oxide gel plugging this joint. Iron oxide deposition is one of the joint-plugging mechanisms in the Coachella Valley.

Tile joint 2 differed in two ways: It showed no brownish-yellow iron oxide or black manganese oxide stains, and it was apparently in a flooded section of the drains. The drain was below grade in the line since water flowed strongly from both sides of the line when it was broken.[8] Water spurted from "blow holes" in joint 2 before the line was broken, but, except for these points, the outer and part of the inner zones of the joint were filled with infiltrated sand, as was joint 1. Some sedimentary micaceous fine sand was found inside the tile.

RESULTS AND DISCUSSION

Particle Sizes, Particle Shapes, and Qualitative Mineralogy of Filter Envelope Materials and Soils

Particles plugging a tile joint might have originated in either the envelope or the the surrounding soil. Their exact nature had to be determined to interpret the materials and particle arrangements found in the tile joints. Table 1 gives the particle-size distributions, and table 2 gives qualitative mineralogies for the gravel filter materials and samples of Mecca soils. Particle and pore arrangements, or fabrics, were observed in thin and thick sections with petrographic and binocular microscopes. Particle-size classes are defined as follows:

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[8]The oasis pit fine gravel and coarse sand filter pack used on these tiles have the same qualitative mineralogical composition as the Mecca soils and are coarser in texture. This filter sand contains significant amounts of micaceous very fine sand, indistinguishable from the soil. The five analyzed soil materials from Coachella Valley have the same qualitative mineralogy.

Particle-size class	*Nominal diameter*
Fine gravel	13-2 mm
Very coarse sand	2-1 mm
Coarse sand	1-0.5 mm
Medium sand	0.5-0.25 mm
Fine sand	250-100 μm
Very fine sand	100-50 μm
Silt	50-2 μm
Coarse silt	50-20 μm
Medium silt	20-5 μm
Fine silt	5-2 μm
Clay	<2 μm
Coarse clay	2-0.2 μm
Fine clay	0.2 μm

Particle arrangement, or fabric terms, are defined in table 3. Terms for identifying various positions in a tile joint are in figure 1. The results of this investigation follow.

TABLE 3.--*Terms for describing microscopic fabrics*

Term	Definition
Joint-jamming grains	Sand grains jammed against both sides of a tile joint. Consequently, progressively smaller grains might be caught.
Skeletal grains	Fine gravel and coarse sand grains braced against each other and forming a rigid network of interstitial pores.
Interstice packing grains	Finer sand and silt grains within the skeletal grain pores.
Micaceous coatings	A thin layer of imbricated fine and very fine sand and silt-sized mica adhering to larger quartz or feldspar grains.
Brace-and-grain fabric	A grain fabric formed by long mica grains contacting and cross-bracing smaller subangular quartz and feldspar grains.
Blockading grains	Small grains, particularly mica, caught in or across interstitial pores.

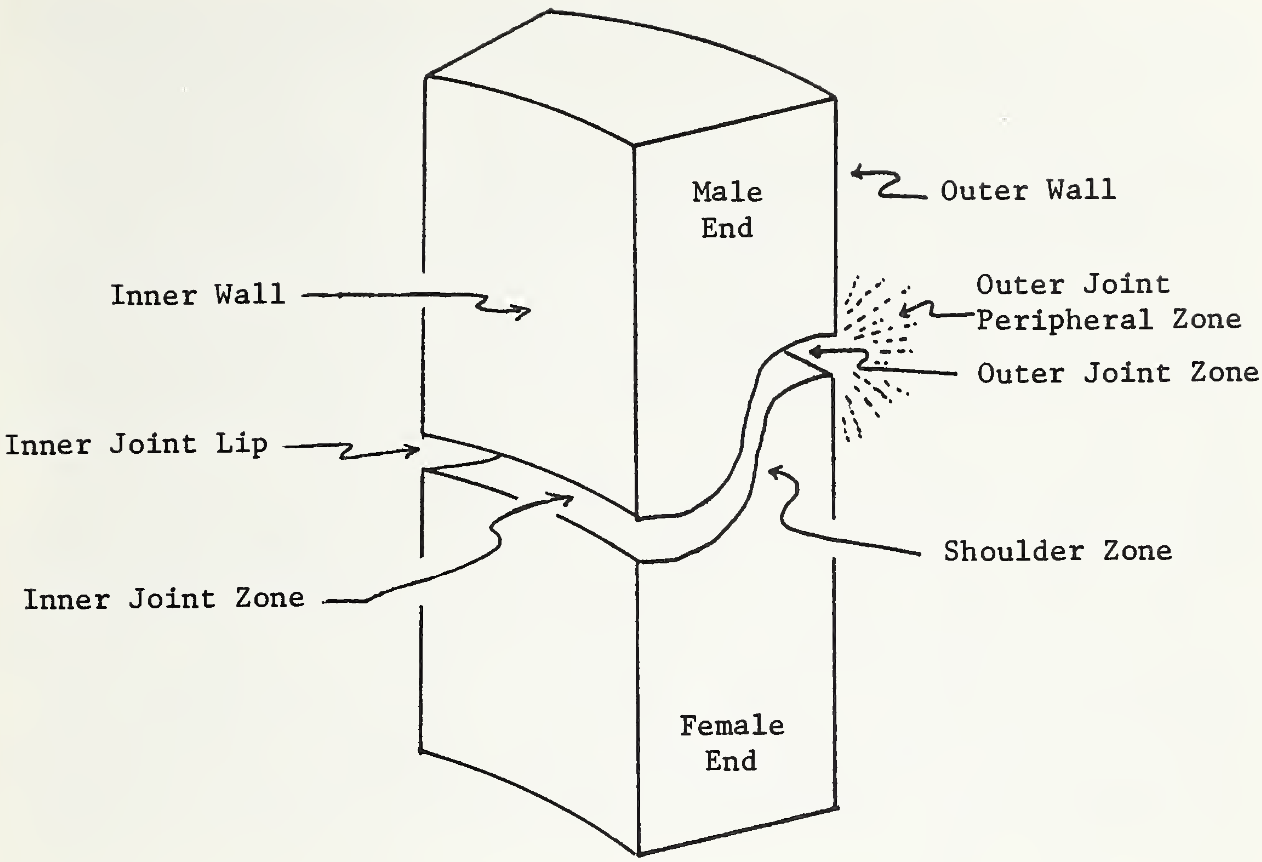

Figure 1.--Terminology for parts of a tongue-and-groove-lip concrete tile joint.

Oasis Pit Filter Envelope Material

The bulk of the coarse filter sand (sample 710) in the Oasis pit is quite clean of clay, silt, and fine sand. In thin sections, the material is evenly size-segregated[9] angular quartz about 1-2 mm in diameter, and very coarse, plagioclase feldspar sand grains. The grains are clean or have about a fifth to a third of their surface coated with a somewhat granular 15-20 μm thick brown material. This material is an amorphous tan matrix containing spherical reddish-brown (apparently iron oxide) segregations of 5-15 μm diameter, some silt-sized mica, and some silt and clay-sized calcium carbonate. This coating is commonly thickest where it forms bridges between coarse sand grains or is limited to one side of a grain. Under reducing conditions, the iron segregates could act as a source of free iron for joint plugging. Some grains are thinly coated with what appears to be opal. Masses of irregular cemented aggregates, 0.1-0.5 mm in diameter, of fine silt-size carbonate, silt-sized mica, fine silt-sized spherical iron concretions, and some clay are present in many of the contact angles between the coarse sand grains. This aggregated material could be confused with infiltrated fines in a tile joint and would act the same. A

[9] Size-segregated particles are all about the same diameter; size-graded particles are of roughly equal proportions of larger, smaller, and intermediate-sized particles.

very few loose, finer sand or silt-sized mica grains are present. Interstices between the sand grains range from 0.25 to 1.0 mm in diameter. Note that the coatings described are quite thin and the pores relatively large and empty.

The finer-sand stratum of the Oasis pit (sample 709) is predominantly composed of very fine sand and coarse silt (table 1). In thin sections, the material is seen to be mineralogically size-segregated, with sharply angular quartz largely comprising the very fine sand fraction of 50-100 μm and the course silt of 50 μm; perhaps a third as much biotite comprises the remainder of the very fine sand of 50-100 μm and most of the fine sand fraction of 100-250 μm. The biotite mica flakes have preferred orientation parallel to the bedding and cleavage planes of the sediment, although numerous mica grains have lodged at various angles between the smaller quartz grains. A few fine sand-sized carbonate aggregates and finer loose carbonate grains are present. The various grains are closely packed; longer mica grains commonly bridge between and contact several quartz grains, that is, brace and grain fabric. Interstitial pores are numerous (roughly 25 percent of volume), roughly equal in size, and roughly spherical; however, they are only 15-50 μm in maximum diameter, and the connections are quite tortuous. Most connecting openings between these pores are only 2-5 μm across. Pore size and tortuousity differences between the coarser and finer sand-stratum fabrics are on the order of 25-100x. Even though these fine materials compose a small proportion of the beach deposits, if they are present as "dirt" in a filter envelope they could be confused with infiltrated soil material since they are of the same mineralogical composition as the soil. Regardless of its immediate source, however, such dirt could act to reduce the permeability of the filter sand pack or might be transported and infiltrated to plug a joint.

Iron-Oxide-Stained Filter Sand Envelope Material, Tile 1

A sample (711) of brownish-yellow Fe-stained envelope material was taken from the joint peripheral zone of joint 1. It has a few percent more silt and clay and several percent more finer sands than does the "clean" coarse sand from the Oasis pit (that is, 710). Thin sections of disturbed material show common, discontinuous, thin (5-30μ), very pale-brown (10YR7/4) to reddish-yellow (5YR7/6) coating of iron oxide. These ovendried, and presumably dehydrated, iron coatings cement some of the fine and medium sand grains to the very coarse sand and fine gravel skeleton, but in their dehydrated form they do not appear to significantly block the 0.5-2-mm-wide interstitial pores of the disturbed filter sand. When hydrated, as in the soil, these iron oxide coatings might well reduce permeability. The bit of calcium carbonate present in a few interstices should not reduce permeability significantly. Thin opal coatings occur on some grains but are probably allogenic and do not appear to act as cement or filling agent.

In both the Oasis pit material and sample of filter sand envelope, the fabric is one of markedly size-segregated coarse sand grains with large, empty, broadly interconnected interstitial pores. These fabrics should offer minimum resistance to saturated waterflow and minimum opportunity for lodgment of suspended mineral grains or closure by accreting oxide gel coatings. This open fabric can be contrasted to some parts of the size-graded sand fillings (that is, with a complete range of particle size) in the tile joints and in the joint outer peripheral zones.

Mecca Soil Materials from Tile Joint Sites

The moderately coarse-to-medium-textured Mecca soils are low in clay and high in highly micaceous very fine sand, fine sand, and coarse silt (table 1 and 2). The qualitative mineralogy is quite similar to that of the filter envelope material from the Oasis pit. The clay fraction is dominated by montmorillonite. Vermiculite, kaolinite, montmorillonite, and biotite occur in the fine silt fraction, although in quite variable proportions in the different samples. Vermiculite and biotite are the most common minerals in the finer silt fractions; biotite is much more prominent in the coarser silts and fine sands. Quartz and feldspar appear in the medium-coarse silt fraction and become dominant in the medium-and-coarse-sand fractions. Kaolinite is not particularly common in any size fraction, although its occurrence in coarser fractions is noteworthy and presumably due to pseudomorphs after feldspar.

In thin sections, the Mecca soil is quite similar in fabric to the finer strata of the Oasis pit. Highly angular, dominantly quartzose, very fine and fine sand-sized grains are randomly interspersed with grains of medium sand-size mica (measured along their long axes). The larger mica grains touch several widely separated quartz grains in a prominent brace-and-grain fabric. In samples 712 and 714, which have relatively low silt and clay contents, the interstitial pores are empty. Although highly irregular in shape, they have their interconnections blocked only by the longer mica grains at irregularly spaced megascopic intervals; interstitial pore sizes range in maximum width from about 50 to 100 μm. Sample 713, which contains 30 percent silt and 8 percent clay, has a more closely packed fabric since it is more nearly size graded, that is, a uniform distribution of coarse to fine particles. Pore sizes are about 30-40 μm in maximum width, and apparently free-floating finer silt-sized and clay-sized mica grains are commonly scattered about in the plastic-filled pores. This could be evidence of particle mobility. The fabric, however, is still relatively open, although the pores are much less prominent than those in the coarse sand from the Oasis pit.

Absence of silicate clay coatings or bridges between sand and silt grains is the most significant feature since it means there is no "cement," however weak, to restrain finer sand or silt grains from dislodging and moving within rapidly flowing water approaching the joints.

Artificial Tile-Joint Plugging

Oasis Pit Very Fine Sand-Water Slurry Filling

Two concrete pipe sections with a butt joint approximately 0.7 mm wide were smeared with the sand slurry, bolted closed, wetted with an eyedropper, and dried several times. After plastic impregnation and sectioning of a thin section, a third of the joint width was seen to be filled with fine sand. The remainder had an even layer, 0.2 mm thick, against what had been the lower side of the horizontally oriented joint. Silt and very fine sand-sized mica grains showed preferred orientation not only to the joint wall where the deposit was thin, but also parallel to the curving walls of vesicles, that is, air bubble cavities, which formed in the sand slurry. This orientation indicates physical freedom of the mica grains to rotate and orient to either solid or water film surfaces during wetting and drying. Where the sand filling was complete, modal

interstitial pore size was about 20 µm. The pores appeared continuous, albeit tortuous, between the closely packed grains. The brace-and-grain fabric (table 3) and finely porous nature of this filling material is quite similar to the fabric of the Mecca soil material except for lack of free silt and clay particles in interstitial pores.

Oasis Pit Very Fine Sand-Iron Oxide and Sand-Iron-Manganese Oxide Slurry Fillings

The tile joint was filled with a viscous slurry of Oasis pit fine sand and thick, gelatinous iron hydroxide, and was then wetted with a dropper and dried several times. It presented a radically different fabric in thin sections. All sand grains were coated with red iron oxide,[10] 5-15 µm thick, and many were cemented together. Where the joint opening was about 1.5 mm, thin coatings of iron-cemented sand adhered to both walls. Where the joint opening was only about 0.35 mm, the paste apparently completely filled the joint, and in these places evidence of iron hydroxide desiccation and shrinkage was prominent; interstitial pores, roughly 50 µm wide, which must have been filled with the hydrated iron hydroxide gel, were open in the ovendried specimens. The residual dehydrated oxide coatings on the sand grains were only about 20 µm thick. Ragged tear-apart edges were common between coated grains. Another evidence of pore filling by hydrated iron oxide gel was the spacing preserved between the sand grains, which was relatively wide in comparison with those obtained with the plain sand fillings described previously.

A third joint, artificially filled with a fine sand Fe-Mn-hydroxide slurry, dried with very similar coatings, bridgings, and cemented grains. The Fe-Mn coating was blackish brown and showed only about 30 percent shrinkage, compared with 50-70 percent shrinkage for the pure-Fe red hydroxide gel.

Thus, there is presumptive evidence that hydrous iron oxide sand coatings, which fill roughly a quarter of the pore volume of ovendried sand-packed tile joint 1, effectively plugged the pores when hydrated.

Water-Transported Sand Filling

A section of 5-inch tongue-and-groove tile, set vertically with the male end on the bottom (that is, water had to flow upward as it passed through the joint into the tile) and encased in Oasis pit filter sand dirtied with 10-percent Mecca-like soil, was plugged during a separate experiment. Thick sections of the joint showed that both the subangular to rounded quartz and feldspar, and the platy mica grains of very fine and fine sand-size, were mobile enough (under the conditions of the experiment) to be infiltrated into the joint and be almost perfectly size-segregated and layered into thin sedimentary strata well within the joint. Portions of the joint were spaced enough to allow medium-sand-sized quartz and feldspar grains to enter and jam in the opening by bridging. These large, separate joint-jamming grains were surrounded with tightly packed very fine and fine sand and silt grains at the joint outer periphery zone; inside the joint, where the joint space was only

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[10]The freshly precipitated ferrous hydroxide gel rapidly oxidized to a red gel, presumably ferric oxide or hydrous oxide.

partially filled with sand, the large grains were only partially buried in stratified finer particles. Where the joint was too tight to allow coarser grains to enter, only the fine and very fine sand were present within the joint.

The mobility of finer sand and silt grains is a necessary deduction from their size-segregated and stratified occurrence within this joint. The tight packing of very fine and fine sand and silt-sized grains of mica and quartz in the interstices between medium-to-coarse-sized sand grains at the outer periphery of the joint can be explained by progressive lodgment of these fine grains. The finer sands preferentially moved into the joint interior without empty interstices being left immediately behind them. If the surrounding filter sand pack has been preserved in the thick sections, comparisons of the degree of interstice filling at the joint periphery and away from it might have provided more decisive evidence of progressive particle infiltration.

Cannell and Week's observations of decreasing flow rates and particle movement (in the next chapter of this report) agree with this microscopic evidence of particle plugging. The visible sediment they saw in the initial drainage water probably moved through the joint at the same time that the initial joint-jamming grains and joint inner sedimentary strata were being emplaced. Their observation of decreasing flow with time, even though drainage water was "clear," probably correlates with progressive lodgment of silt particles in the joint outer peripheral zone. Their observations on joint filling and lodgment of fines in the joint outer peripheral zone are similar to those reported above.

Joint Filling and Plugging Materials in Tile Joints 1 and 2 from Mecca Soils

Technical Problems

Positive identification of plugging and filling materials required several different study techniques. Ordinary thin sections (20-40 μm thick) did not provide the three-dimensional view of silt and fine sand grains needed to establish their effective positions. Polished sections 2-3 mm thick, with cover glasses cemented on, provided an excellent view of pore organization and filling; however, in the smaller and more tightly packed pores, particle size and arrangements are difficult to determine against background patterns. A thick-thin section, roughly 70 μm thick (second-order blue quartz interference color), proved the most useful section in combination with the others. Grains larger than coarse silt or very fine sand are somewhat flattened in such a section; most silt and very fine sand is untouched and can be seen in full relief.

The petrographic microscope with transmitted-light illumination was found ineffective for some elements of fabric analysis. The depth of focus is too shallow; three-dimensional patterns and inclined grain margins cannot be seen. A necessary companion tool proved to be a stereoscopic microscope with incident illumination from a "high-intensity" desk lamp. It was particularly valuable in resolving relatively large inclined thin mica grains from a tan blur to distinct objects. Reddish-brown free iron oxide coatings and white opal coatings on grains are much more obvious and are normally colored under incident light, whereas with transmitted light they may merely look gray and of indistinct position.

A third difficulty arose from a dislocation of the joints by 2-3 mm that occurred during sampling in both the longitudinal and lateral directions. Fortunately, a considerable part of the joint-filling material was preserved in masses or positions arranged such that the original position could be inferred. For instance, many of the size-graded compact sand fills of the joint outer zone rested tightly on one joint curving tile wall face and had an equally smooth and curving free face which exactly paralleled a like curving tile-wall face 2-3 mm away; such an accommodating face is evidence of lack of disturbance to the sandy fabric. Torn plugs of iron and manganese-oxide-cemented grains, with matching ragged faces or partially connected grains, were common in joint 1. Tensional separation of sandy fills in some joints left accompanying ragged tear-faces. Partial dislocation, rotation, and translation of coarse grains in finer matrices could be established by face-and-mold relations where movement was not excessive. In summary, the slight joint dislocations did not prevent analysis and interpretation of these natural joint-plugging materials in place.

Evidence of Sand Infiltration

Joint outer zones and outer peripheral zones.--Joints 1 and 2 had their outer joints filled with size-graded fine gravel to silt-sized particles. The joint outer zones contained a rigidly packed fine gravel and coarse sand-sized skeleton which was merely an extension of the skeletal framework of the coarse sand filter of the joint outer peripheral zone. This framework was formed of the examined Oasis pit filter sand samples. The Oasis pit material, however, was large, with pores of 200-700 μm diameter, which are made smaller only by the discontinuous adherent coatings, 15-20 μm thick, described previously. In comparison, the interstitial pores of the skeletal grain framework in the outer joints were densely packed with medium, fine, and very fine sand-sized quartz, feldspar, and mica grains (that is, size-graded).[11] At higher magnifications, the very fine and fine sand-sized grains and some coarse silt-sized mica grains are particularly prominent elements of this joint-filling sand since they lie against the larger skeletal grains in a shingled continuity. At lower magnifications, the coarser sand merely looks dirtied, and the mica grains are not recognizable as plugging grains. Median pore size in this size-graded joint-filling fabric is 10-70 μm, compared with pores of 200-700 μm in the clean filter sand.

Effective pore size, as a result of infiltration of fine sand and mica blockading, might be small enough to cause a pore-sized controlled tensional barrier to waterflow at the air-water interface inside the drainage tile. These interstice-packing fine and very fine sand grains in the outer joint zone and its peripheral zone are presumably infiltrated and concentrated. They are representative of either the most common grain sizes and mineral types in the Mecca soils or the "dirt" in the Oasis pit filter sand. There is evidence that very fine sand and coarse silt is infiltrated or at least concentrated within the filter sand at this critical entrance to the tile joint. Not only do the samples of the clean, coarse Oasis pit sand have large, open pores, but the

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[11]The numerous mentions of mica grains might leave the impression that only micaceous grains are involved in plugging. Also quite prominent as interstice filling and blockading grains, however, are fine and very fine sand-sized angular to rounded quartz and feldspar.

samples of iron-stained filter sand taken within 2 inches of joint 1, and samples of unstained filter sand taken several inches from joint 1 also have open, large interstitial pores not continuously packed and jammed with finer sands. Since the skeletal sand grains in the joint outer zone had to be filter sand which was pushed into the joint, it should have first consisted of largely empty interstitial pores. These pores must then have been filled with transported finer grains for the packing density to be of the type observed.

Joint inner zones.--The joint inner zones of both tile joints were empty except at the bottom of the drain. There the joint inner zone was filled with fine and very fine sand and silt, presumably trapped as it washed along inside the tiles. Sedimentary bedding of mica was prominent in some sections.

This sedimentary bedding in the bottom of the inner zone of tile joint 2 (which was filled with water when excavated, and showed no iron oxide staining in or around the joint) would probably not be preserved if water had been flowing into the joint. Therefore, the preserved bedding is at least circumstantial evidence that joint 2 was effectively plugged by infiltrated sand and silt in its outer zone.

Iron and manganese oxide plugging in joint 1.--This joint was probably first plugged by infiltrated sand grains. It was plugged by hydrated iron oxide gel in the joint outer zone and shoulder zone, and by manganese dioxide and iron at the joint inner lip. Moderately thick red iron coatings and bridges of sand grains were common in the joint outer zone and shoulder zone. A layer of dehydrated iron, 0.1-0.2 mm thick, coated the walls of the shoulder zone and joint inner zone in many sections. This coating extended to the joint inner lips and a few millimeters beyond. At the joint inner lip, the iron coating was itself covered with a black, granular to powdery layer of manganese dioxide, 0.1-0.3 mm thick, which extended onto the walls of the joint inner zone only. At the joint inner lip, a plug of iron, manganese, and entrapped fine sand grains closed the entire circumference of the joint. Although the reddish-brown iron oxide did not fill all pores in the sections studied, the coatings were thick enough in their presumably dehydrated form that they should have blocked pore continuity in their original hydrated state.

The hydrated iron oxide gel was apparently deposited after sand infiltration but before manganese dioxide deposition and at lower oxidation states than the manganese dioxide. It occurred on sand grains in the joint outer peripheral zone, on the joint walls and sand grains in the joint, and beneath the manganese dioxide deposit at the joint inner lip. The manganese dioxide deposits were a redundant plugging material.

SUMMARY AND CONCLUSIONS

Undisturbed tongue-and-lip joints from two inoperative concrete drainage tile lines in a low-clay micaceous Mecca soil of the Coachella Valley were examined in petrographic thin and thick sections for identification of joint-plugging materials. The joint outer zones of both were plugged with size-graded finer sand and silt like those in the Mecca soil. One joint was also plugged with hydrated iron oxide gel. The filter envelope material used

locally is contaminated with finer sands and silt, which, like those of the Mecca soils, also could be transported and deposited in the tile joints.

Drainage-line design to prevent joint plugging (in this situation) should reflect the character of the soil. The soil is high in very fine sand and silt which is not bound in aggregates by clay; hence they are potentially mobile in rapidly moving water. Periodic reducing conditions in the soil caused by restricted drainage produce soluble ferrous iron, which can then be precipitated as viscous plugging gels in the oxidizing environment of a tile joint.

Figure 2.--The immobilized concrete tiles used to study joint-plugging materials. Note the blackish-appearing hydrous iron oxide deposits on end of near set of tiles (joint 1) and the gauze-and-tape-covered joint opened for plastic impregnation.

Figure 3.--A thick-section from upper half of tile joint 1. The outer joint zone is filled with size-graded sand and silt, the inner joint zone is empty. The open (black) space in the outer joint zone is the result of a slight dislodgment of the joint during removal and transport; note how the torn surface of the packed sand grains conforms to the opposed tile face. The cut concrete tile surface appears whitish.

Figure 4.--Brace-and-grain fabric of very fine sand and silt grains. The flat-appearing long grains are mica seen in cross section; the angular and sub-angular grains are quartz and feldspar.

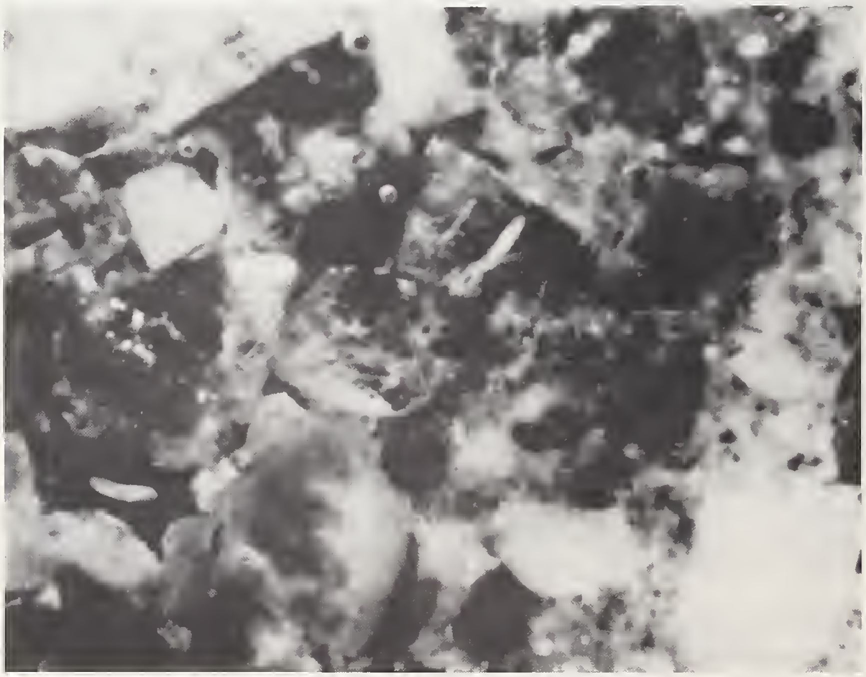

Figure 5.--Size-graded sand and silt entrapped in the outer zone of joint 2. The fuzzy white coatings and bridges between the grains are silt-sized mica unresolved at this magnification.

LABORATORY EVALUATION OF FACTORS INFLUENCING PARTICLE MOVEMENT INTO DRAINS[1]

By Glen H. Cannell and L. V. Weeks[2]

INTRODUCTION

In the Coachella Valley of southern California, the discharge from a large number of drain lines is much less than the design capacity. Standing water can be measured above affected drain lines during irrigation, and the water table persists above the drains for prolonged periods after water application. The soils in the area are coarse to medium-textured, with layers of varied thickness. Layers of fine sand in the upper part of the soil profile frequently contain small quantities of silt and clay. The general unstructured characteristics of coarse-textured material dominate the soil profile where the drains are placed, necessitating envelope materials in drain placement. The envelope materials are obtained from gravel pits in the area, particularly the Oasis gravel pit. The material is naturally graded in the size range of 0.5 percent < 0.105 mm and 1.2 percent > 6.35 mm, but with considerable variation in the percentages of the larger or fine materials.

Envelope material is stockpiled in the field before the drains are constructed. In reloading the material during drain installation, fine soil materials are often inadvertently included in the envelope material being placed around the drains. Thus, the quantities of fine materials incorporated in the drain envelope may vary from both the gravel pit and the loading process.

The placement of envelope materials containing various quantities of fine particles raises the possibility of particle movement within and through the envelope, and, finally, into the drain through the drain opening. Bridging of the particles may effectively plug the drain opening.

Drainage-model studies were conducted in the laboratory to study factors related to the behavior of drain envelope material under conditions in the Coachella Valley.

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[1]Contribution from the Citrus Research Center and Agricultural Experiment Station, Riverside, Calif. These studies were supported in part by Western Regional Project W-51, "Drainage Design for Irrigated Agriculture."

[2]Soil physicist and staff research associate, respectively, Department of Soil Science and Agricultural Engineering, University of California, Riverside.

MATERIALS AND METHODS

Of several types of laboratory models constructed and tested, two were used in most of the studies (figs. 1 and 2). Concomitant with the longtime laboratory studies using the model in figure 1, tests were conducted with small transparent plastic models 10 cm in diameter and 20 cm in length. The small models were designed for flow vertically upward using hydraulic gradients from 1 to 4. A loamy sand from the Coachella Valley was used as base material, and various types of envelope materials were evaluated, including pea gravel, Oasis pit gravel, pit gravel (from Imperial Valley), Oasis pit gravel > No. 16 screen, and "chat" (pit gravels with fines removed) (table 1).

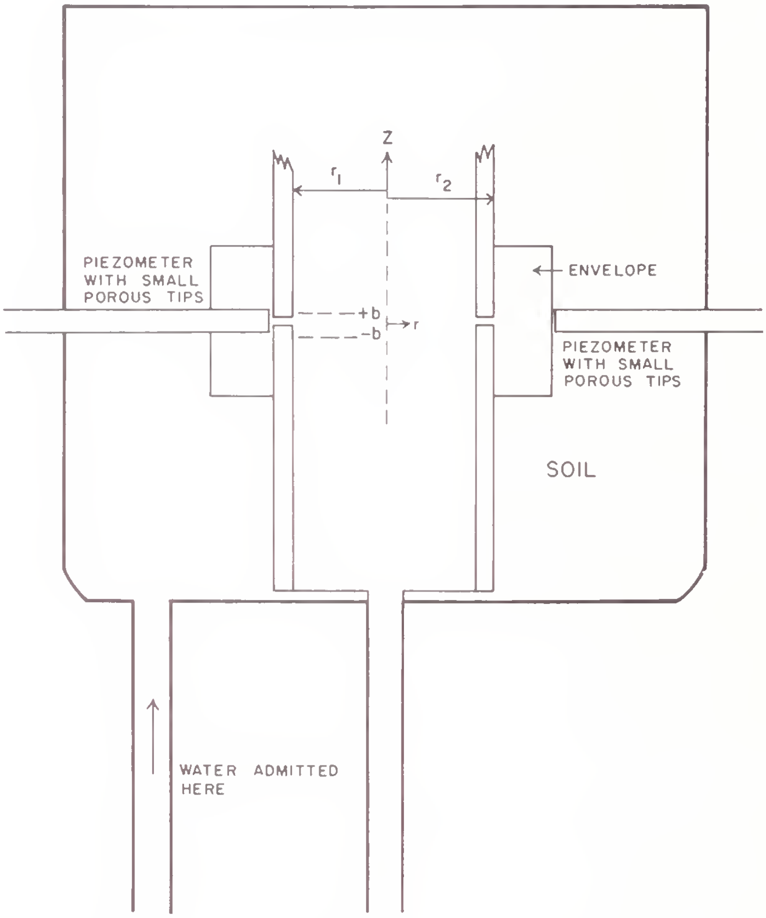

Figure 1.--Schematic drawing of laboratory drainage model use with tile and tongue-and-groove pipe (dimensions in text).

The outside cylindrical tank in figure 1 is polyethylene plastic, 36 cm in diameter and 50 cm high. Studies with the tank were conducted with two sections of drain tile (12.8 cm ID) with flat ground ends and also with tongue-and-groove concrete pipe of the same diameter. The tiles were clamped together with a predetermined joint space and were then positioned with their axis vertical at the center of the tank. The concrete pipes were positioned in a similar way. Envelope material was placed around the joint inside temporary forms, and the remaining part of the tank was filled with a selected base material. Small

ceramic-tip manometers, sensitive to slight water pressure changes, were placed at the drainage opening and at the interface of the envelope and the base material. Water was admitted from the bottom of the tank, with the head controlled to allow some overflow above the soil. The overflow and flow into the tile through the joint were returned by a pumping system to a supply tank and recirculated.

Figure 2.--Section of plastic drainage model showing envelope material and drain tube. Other sections are attached at top or bottom of unit (dimensions in text).

Two pieces of clear plastic pipe (2.5 cm ID), simulating drain tiles with smooth ends, were positioned nearly horizontally through the walls of a vertical plastic tube at the midpoint of a 15-cm length of the tube (fig. 2). Additional tubes were fastened to the lower end of the 15-cm section so that the total length of vertical column was about one meter. Open manometers were installed at several positions along the vertical tube, and ceramic-tip manometers were placed at the drainage opening and at the envelope-base material interface. A drainage gap was formed by placing three small brass shims 120° apart between the ends of the two pieces of horizontal pipe. Some similarity between the model and tile drain pipes (13.7 cm OD) was obtained by adjusting the gap width of the model so that the ratio of the outside circumference of the pipe times the gap width was similar to the ratio for two tile drain pipes laid end-to-end. Envelope material was placed around the horizontal pipe, and base material was placed below the envelope. Fluid flow was maintained either by a return pump or by a tap-water-pressure system so devised as to remove

entrapped or dissolved air from the water before it enters the soil column. Flow was vertically upward through the base material, the envelope, and then through the gap and out one end of the drain pipe. The hydraulic gradients (HG) across the system were adjusted to control the average fluid velocity through the drain opening so that particles near the gap might be transported toward and/or into and through the gap. For envelope materials composed of particles with effective diameters greater than the gap width, any material that entered the gap and pipe would have been transported through the envelope from the base material. Envelope materials of different particle-size distribution and envelope thicknesses were also tested with a base material of loamy sand from Coachella Valley. Hydraulic gradients were applied across the materials and were increased in small steps from values of less than one to those required to produce some visual evidence of particle movement into the drain or into the envelope materials. If a given hydraulic gradient had no noticeable effect, and if the average velocity of fluid through the gap was in the range of 1 to 2 cm/sec, that particular gradient was maintained for 8 to 9 h/day for several days.

TABLE 1.--*Particle sizes and percentage values for envelope materials and a loamy sand*

Material	Size classes (mm)							
	>9.5	0.5-6.4	6.4-4	4-2	2-1	1-0.5	0.5-0.25	0.25-0.1	<0.1
	Percent								
Pea gravel	3	75	21	0.7	0.3				
Coachella Valley pit gravel			6	12	39	35	5	1	2
Imperial Valley pit gravel			4	10	38	29	5	9	5
Coachella Valley pit gravel > #16 screen[1]			8	22	55	14	.5	.3	.2
"Chat"[1]			24	48	14	8	1	3	2
Loamy sand					2	2	2	48	46

[1] Commercial products; pit gravel with some fines removed by screening.

Three methods were used in an attempt to determine whether drain openings were plugged with particles: (1) visual inspection after removal of envelope material, (2) solidifying particles in place with clear casting plastic, and (3) photographs taken from inside the plastic drain of figure 2. For visual inspection of the opening, envelope material was carefully removed with small spatulas. Preparatory to solidifying the particles in place with clear casting plastic, circular separators of thin plastic were placed perpendicular to the drain, spaced 2.5 cm apart. The plastic pieces were made in two equal sections and joined along the common diameter, base material was removed from the outside following drainage, and adhesive tape was place around the 2.5-cm-thick

plastic material to hold the envelope material in place. The unit was allowed to air-dry, and then casting plastic was poured into the unit at various places from the outside. Upon drying, the unit was separated longitudinally into two equal units for examination of the drain opening. For making in-situ photographs, a 45°-angle mirror prism was attached to a movable plastic rod that was held in a larger piece of plastic that fitted closely to the outside of the plastic drain tube. By sliding and turning the mirror inside the drain tube, the drain opening and adjacent areas along the tube could be seen reflected on the prism mirror. A piece of film adjusted to fit inside the drain tube was numbered consecutively from 0 to 360° in 30° units. By proper adjustment of light and mirror, a succession of seven pictures were taken from the opposite end of the drain tube. The finished pictures were then cut and cemented together to show the complete drain opening circumference. The complete picture was an enlargement five times the original.

RESULTS AND DISCUSSION

Tile Drain

A set of observations were made with plaster sand as the base material, and two filter mixes were made by modifying the plaster sand with 10 and 20 percent of a structureless soil (60 percent silt and clay). Four models of the type shown in figure 1 were used with tile, two with joint spacings of 0.06 cm and two with joint spacings of 0.03 cm. The total hydraulic head was controlled at 33 cm above the tile joint.

The data show a general trend toward decreasing flow rate with time for each of the treatments (table 2). Flow rates were higher for the 0.060-cm joint opening than for the 0.03-cm opening with both the 10 and 20 percent additions of fine materials added to the drain envelope. For the 0.06-cm opening, the flow rates were considerably less for 20 percent fine material added than for 10 percent added. Flow rates for the 0.03-cm opening were nearly the same for both envelope mixes after the first few hours of operation. Although flow rates differed between the 10 and 20 percent envelope mixes, decreases in flow rate with

TABLE 2.--*Flow-rate variations with time for plaster sand envelope material augmented with 10 and 20 percent structureless soil (60 percent silt and clay) using 12.8-cm-ID tile with two joint spacings of 0.060 and 0.030 cm*

Time (hours)	Percentage of envelope material augmented with structural soils for the following joint spacings (in parentheses)			
	10 (0.06 cm)	20 (0.06 cm)	10 (0.03 cm)	20 (0.03 cm)
	Cm³/min			
0	364	200	248	116
22.5	304	100	16	16
119	540	216	14	16
492	348	88	12	12
942	240	44	12	12
1400	200	44	12	12

time were about the same. Initially, some fine materials were collected in the drain, but after several hours of drainage the water became clear. Most of the rearrangement and stabilization of particles apparently takes place within the drainage envelope during the first few hours of drainage. Nevertheless, the continued decrease in flow rate with time indicates possible further displacement of particles within the drain envelope or a decrease in the sizes of the larger pore spaces.

Because the short-time experiences (table 2) showed a tendency for decreasing flow rate with time for the materials used, it was decided to conduct longer experiments and increase the number of treatments by using different envelope materials with loamy sand from the Coachella Valley as base material. These procedures would simulate field conditions to some extent and offer a wider range of data for comparison. Used in these studies were eight drainage models of the type shown in figure 1, including two replications of pea gravel and gravel > 0.59 mm. Hydraulic head was controlled at 33 cm above the tile joint. Recorded periodically were hydraulic head values at two locations in each model; the volume, Q, of liquid that flowed through the tile joint in unit time; and the water temperature.

An equation[3] that describes radial liquid flow between two parallel disks was tested for the system using water only in each of four separate models that had gap widths of 0.015 cm. If a parabolic velocity profile in the smooth butt joint (fig. 1) is assumed, then the equation

$$Q = \frac{4\pi \Delta p \; b^3}{3\mu \; \ell n \; r_2/r_1} \tag{1}$$

describes liquid flow through a tile joint for small Reynolds numbers ($Re = 2b\rho\bar{v}/\mu$). In equation 1, Q is the quantity of liquid that flows through the joint in unit time; $\Delta\rho$ is the pressure difference (at the joint level) between r_2 and r_1, the outer and inner radii of the pipe; b is one-half the gap space; μ and ρ are fluid viscosity and density, respectively; and $\bar{v}$ is the average flow velocity through the tile joint in the r direction. With a gap width of 0.015 cm, values of Q and Δp were such that $2b$, the average gap width calculated from

$$b = \left(\frac{3Q\mu \; \ell n \; r_2/r_1}{4\pi \Delta p} \right)^{1/3} \tag{2}$$

was 0.016 cm. Reynolds numbers of 60 and 70 were calculated for the flow conditions. Considering a nonparabolic velocity profile, as for turbulent flow, for example

$$\bar{v}\;(r,\; z) = \frac{\Delta p \; b^2}{2\mu r} \; \ell n \; r_2/r_1 \; \left(1 - \frac{z}{b}\right)^{1/7} \tag{3}$$

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[3] Bird, R. B., W. E. Stewart, and E. N. Lightfoot. Transport phenomena. John Wiley and Sons, p. 114. 1960.

then

$$b = \left(\frac{8Q\mu \ \ln r_2/r_1}{15.4\pi\Delta p}\right)^{1/3} \tag{4}$$

and the average calculated value of $2b$ = 0.014 cm. The agreement between the calculated and experimental values of gap spacing justifies the use of equation 1 or 2 in analyzing experimental data in the studies involving envelope and base materials where values of Q, p, and water temperature change with time and the Reynolds numbers are less than 9.

Effective gap spacing ($2b$), calculated from equation 2, showed large differences between treatments with time but only small changes within treatments (table 3). For soil only (no envelope), Oasis pit gravel, and pea gravel, the calculated values of effective gap spacing decreased slightly with time following measurements on the third day. For plaster sand (pit gravels > 0.297 mm and > 0.59 mm) the values increased slightly after the third-day measurement but tended toward stable values after one month. The pressure difference (Δp), measured at only one point at the joint opening, was used to represent the entire gap space. The rearrangement of particles in the envelope during drainage could change Δp at the measuring point enough to account for small variations in the calculated values. The decreasing values in effective gap for soil (no envelope), Oasis pit gravel, and pea gravel suggest a possible continued rearrangement of particles in the drain envelope with drainage after the 3-day period. For the remaining treatments, the effective gap would appear to be fairly constant after one month. In all treatments, however, most of the particles were collected during the early stages of drainage, which indicates that the major rearrangement of particles takes place largely during the first few days of drainage.

TABLE 3.--*Calculated effective gap spacing for continuous liquid flow for various envelope materials using 12.8-cm-ID tile with a joint spacing of 0.015 cm*

Envelope material	3 days	1 month	4 months	11 months
	Cm x 10³			
Loamy sand (no envelope)	4.4	3.3	2.8	
Plaster sand	8.3	9	12	11
Oasis pit gravel	30	30	23	24
Oasis pit gravel > 0.297 mm	14	17	17	14
Oasis pit gravel > 0.59 mm	14	16	17	14
Washed pea gravel	8.2	8	13	9

Average flow rates determined at various times for the continuous tests showed that flow rate decreased with time (table 4). The study was continued to 16 months, and during that time the flow was periodically interrrupted. Flow was maintained 96 h of each 168-h period. The flow rates were about the same for intermittent flow as for constant flow. At the conclusion of the 16-month period, the models were disassembled and the envelope material and the joints examined visually. Base material had entered the pea-gravel envelope but appeared to be excluded from entering the plaster sand, Oasis pit gravel, and screened pit gravel (> 0.297 mm and > 0.59 mm). For pea gravel, 275 g of base material was collected in the drain water during the first 4-month period. The material collected in the drain was < 250 µm in diameter, and 77 percent was < 0.01 cm in diameter. Particle movement in the pea gravel was associated with relatively high outflow rates and probably with large base-material conductivity. The latter could not be determined readily in the models, because of the curvilinear nature of the flow lines. A few particles were trapped in the drain gap opening in each treatment. The full effect of particles blocking the pathway into and through the drain opening could not be determined, since the position of the particles surrounding the drain opening was disturbed when the apparatus was dismantled to observe the envelope material.

TABLE 4.--*Flow rates with times for various envelope materials using 12.8-cm-ID tile with a joint spacing of 0.015 cm*

Envelope material	1 month	4 months	11 months
	------------*Cm³/min*------------		
Soil only (no envelope)	12	7.2	--
Plaster sand	96	72	24
Oasis pit gravel	96	78	25.8
Oasis pit gravel > 0.297 mm	66	48	30.6
Oasis pit gravel > 0.59 mm	59.4	36.6	18.6
Washed pea gravel	185	137	83.4

Additional studies were made of the large laboratory drainage models with concrete tongue-and-groove pipe (12.8 cm ID) with an effective gap width of 0.10 cm (calculated using equation 2). Several short-time studies were made with the same envelope materials that were used with the tile-drain sections. The results were similar to those obtained in the tile-drain studies. With pea gravel, particles moved into the drain envelope and some particles were collected in the drain.

Small Drainage Models

Concomitant with the long-time drainage, runs were tested with small drainage models (previously described) to determine the effect of hydraulic gradients on particle movement. Studies were made on loamy sand used alone as base material and with various envelope materials placed on the base material to simulate a drainage envelope.

A column of porous material of length L, may become weightless when frictional drag per unit area on the particles equals the effective weight per unit area of the particles. That is, when

$$\rho\, g\Delta H = L \left(\rho_b / \rho_s\right)\left(\rho_s - \rho\right) g \qquad (5)$$

where ΔH is the hydraulic head difference across the column, ρ_b is the average bulk density of the material, ρ_s and ρ are the particle and liquid densities (ρ_s is assumed to be 2.66 g/cm^3), and g is the acceleration due to gravity. If a load is placed on the upper column surface, then a term equivalent to the effective weight per unit area of the load should be added to the right-hand side of equation 5.

The columns were packed at different bulk densities. The hydraulic gradients were measured and were also calculated with equation 5. For an increase in bulk density of the loamy sand column, the hydraulic gradients value at which the column became weightless tended to increase linearly over the range of ρ_b (table 5). Where bulk density (ρ_b) was held constant and column surface loads

TABLE 5.--*Measured and calculated hydraulic gradients across columns of loamy sand at differing average bulk densities with no surface load when particle transport occurred during upward water movement*

Bulk density (g/cm^3)	$\Delta H/L$ measured	$\Delta H/L$ calculated	Δ difference
1.20	0.73	0.75	0.02
1.25	.79	.78	.01
1.28	.90	.80	.10
1.30	1.19	.81	.38
1.32	1.26	.82	.44
1.33	1.31	.83	.48
1.37	1.55	.85	.70

were varied for the different envelope materials, the hydraulic gradients increased linearly with increasing ratio (R) of load to soil (table 6). At the same load levels, particle movement occurred at much smaller hydraulic gradients for pea gravel than for the other envelope materials. This indicates that particles can move from the base material into the envelope material under certain drainage conditions. The movement of particles at the measured hydraulic gradients supports the data obtained in the large drainage models that had similar hydraulic gradients. Some particles moved into the envelope and some into the drain.

The small drainage model (fig. 2) was used (1) to check data obtained with the large drainage model (fig. 1), (2) to study the effects of higher flow velocities on transport of base material and envelope material, and (3) to extend the data.

TABLE 6.--*Measured and calculated hydraulic gradients across columns of loamy sand of the same bulk density (1.25 g/cm³) with surface loads when particle transport occurred during upward water movement*

Type of envelope material (load)	$\Delta H/L$ measured	$\Delta H/L$ calculated	R Load/soil
Pea gravel	3.13	1.66	1.13
	4.69	2.44	2.15
	.79	.78	0
Oasis pit gravel	2.50	1.39	.79
	.79	.78	0
Imperial Valley pit gravel	2.63	1.42	.84
	3.44	1.71	1.20
	4.53	2.16	1.78
	.79	.78	0
Oasis pit gravel	2.38	1.38	.78
	.79	.78	0
"Chat"	2.00	1.12	.56
	2.34	1.21	.69
	2.40	1.32	.70
	.79	.78	0

Envelope materials > 0.043-cm gap width.--For pea-gravel envelope (mean diameter 0.68 cm) with a base material of loamy sand, particle movement through the gap began when average fluid velocity through the voids of the gravel was 43 cm/h and the hydraulic gradient across the base material was 5.8. The gradient was increased in small steps to a maximum value of 11, and the corresponding mean void velocity through the gravel was increased to 69 cm/h. The increased velocity caused a large number of fine particles to enter the drain pipe. The maximum effective diameter of the fine materials was less than 15 μm, and these were swept through the gap with average flow velocities of 3000 cm/h (for HG = 5.8) and 4800 cm/h (for HG = 11). No particles were lodged in the gap. About 10 g of material was collected in the drain.

In one test, the loamy sand base was screened to remove particles < 53 μm and then used as a coarse base material. Oasis pit gravel > 1.00 mm was used as envelope material. Hydraulic gradients approaching 2.0 were reached in this test, and no fine material was transported through the envelope into the drain.

To transport 60-μm particles through unobstructed spaces requires a velocity of 1400 cm/h. The porosity of the envelope was estimated to be 0.4, and an average flow velocity tc move the particles was 560 cm/h. The average flow velocity in this study was about 23 cm/h; a velocity of 560 cm/h would have required a hydraulic gradient of about 24.

Envelope material with some particles < 0.028-cm gap width.--A loamy sand soil was used as base material, and Oasis pit gravel plus 10 percent of the

base soil was used as envelope. The mix contained 15 percent particles < 250 µm. The hydraulic gradients were increased from 0.5 to 6.4 over a period of 10 days. The gap velocity increased from 143 cm/h to 1938 cm/h. Particles with mean effective diameters of 270 µm will be transported with the latter velocity when they are free to move. Particle movement into the drain was considerable during the 10 days of the test. The total weight was not obtained, because "eruption" or a quick condition of the soil column occurred when the hydraulic gradient approached 7. Results were similar since Oasis pit gravel mixed with 25 percent sandy loam (24 percent) < 250-µm fine material) accumulated in the drain when the gap velocity was 1520 cm/h (transportable particles < 60 µm). Increasing the velocity to 5300 cm/h (transportable particles < 125 µm) over a period of several days results in clear effluents. The larger particles transported with higher velocity were possibly trapped in the envelope material and formed a network of small spaces that effectively prevented further movement of the finer particles.

Gravel from the Oasis pit was screened to remove particles < 250 µm, which were re-added to the screened gravel to obtain envelopes with percentages of fine materials to 5, 10, 15, and 20 percent of the total. The base material adjoining the envelope averaged 1 to 2 mm in diameter. By using a coarse material for the base, high flow velocities could be obtained without eruption or "lifting" effects on the column. Particle transport would then come only from the envelope material. The drainage tests were duplicated, and measurements were taken for a 6-h period each day for 5 days. Each run was begun with low flow rates and increased in small increments until a high rate in each treatment was reached. This was maintained through the gap opening (0.081) for the remaining part of the 6-h period.

The hydraulic head loss (measured just outside the gap and at the envelope-base material interface) increased linearly with flow rate for each treatment and was highest for the 20 percent fines treatment (fig. 3). The quantity of fine material removed by drainage increased with the amount added to the envelope. After the final drainage run, the measured percentage of fine material remaining in the envelope was 4, 8, 12, and 15 percent, compared with the 5, 10, 15, and 20 percent added initially. Large amounts of fine material remained in the envelope in the treatments of high percentage of fine material added, thus influencing the flow rates. Figure 4 shows the particle arrangement in and around the drain both after drainage with 5 and 20 percent fine material added, and before drainage with the 20 percent treatments. The photographs in figure 4 were made with the prism reflector described earlier.

More particles are lodged in the gap with 20 percent fine material than with 5 percent. Numerous smaller particles are also trapped in the envelope, particularly in the 20 percent treatment. Rather large pockets of fine materials can be observed on either side of the gap. The effect of these on flow properties is not known, but the amounts located close to the drain opening increased with increased level of fine material added to the envelope. These pictures and those for 10 and 15 percent (not shown) clearly indicate that the drain openings are not "plugged" with particles. Fine materials are trapped in the envelope, reducing the pore size and thus altering the flow properties.

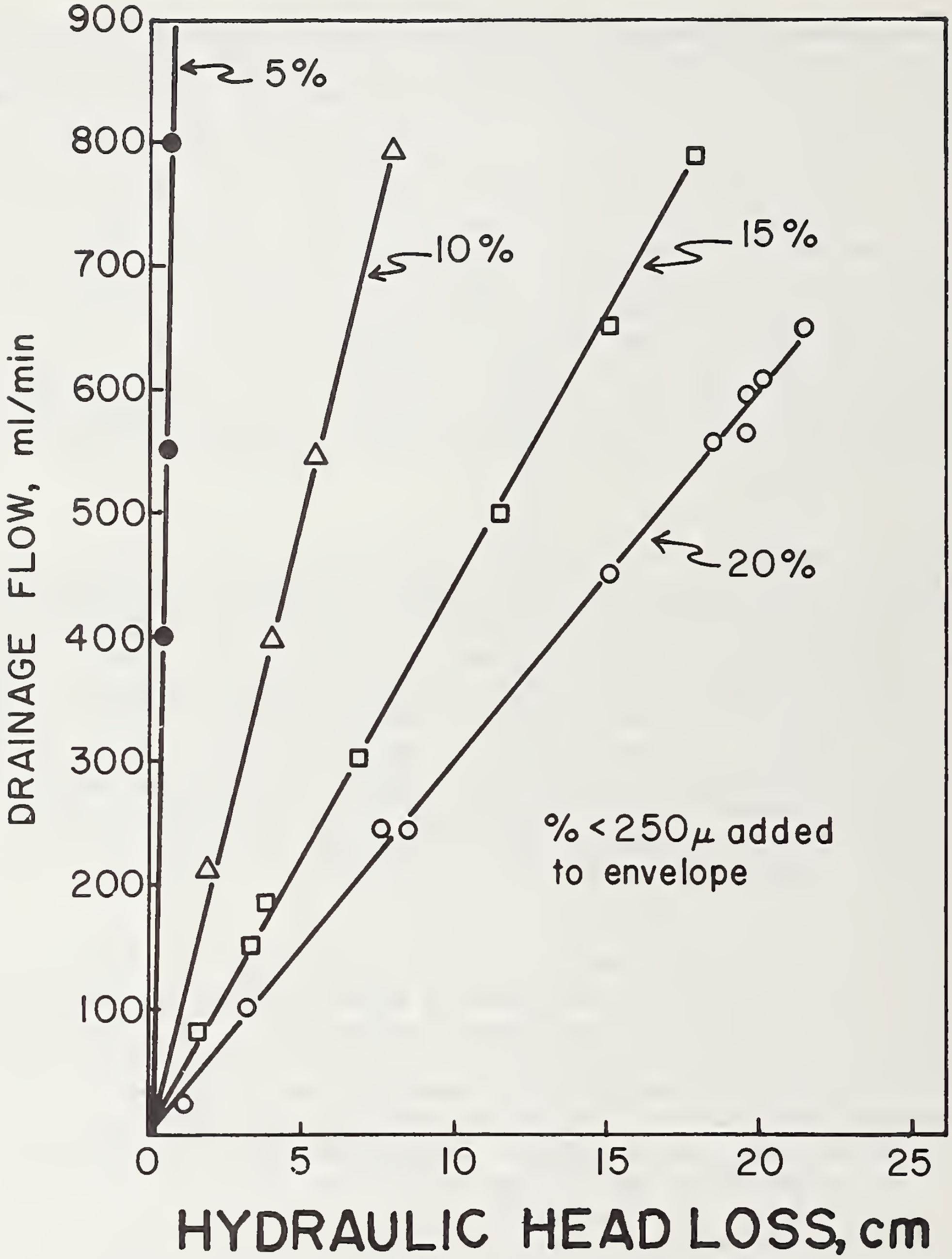

Figure 3.--Flow rate and hydraulic head loss for different percentages of fine material < 250 μm added to Coachella Valley pit gravel > 250 μm envelope material.

SUMMARY AND CONCLUSIONS

Laboratory tests conducted on different base and envelope materials in two types of models have shown that fine soil particles do move in and through drain envelopes. If envelope pores are large, particles can move easily. Photographs of drain gap openings show that plugging of the actual gap was not the cause of decreased drain discharge. The problem seems to occur when fine particles move within the envelope material, clogging and reducing the area of large pores.

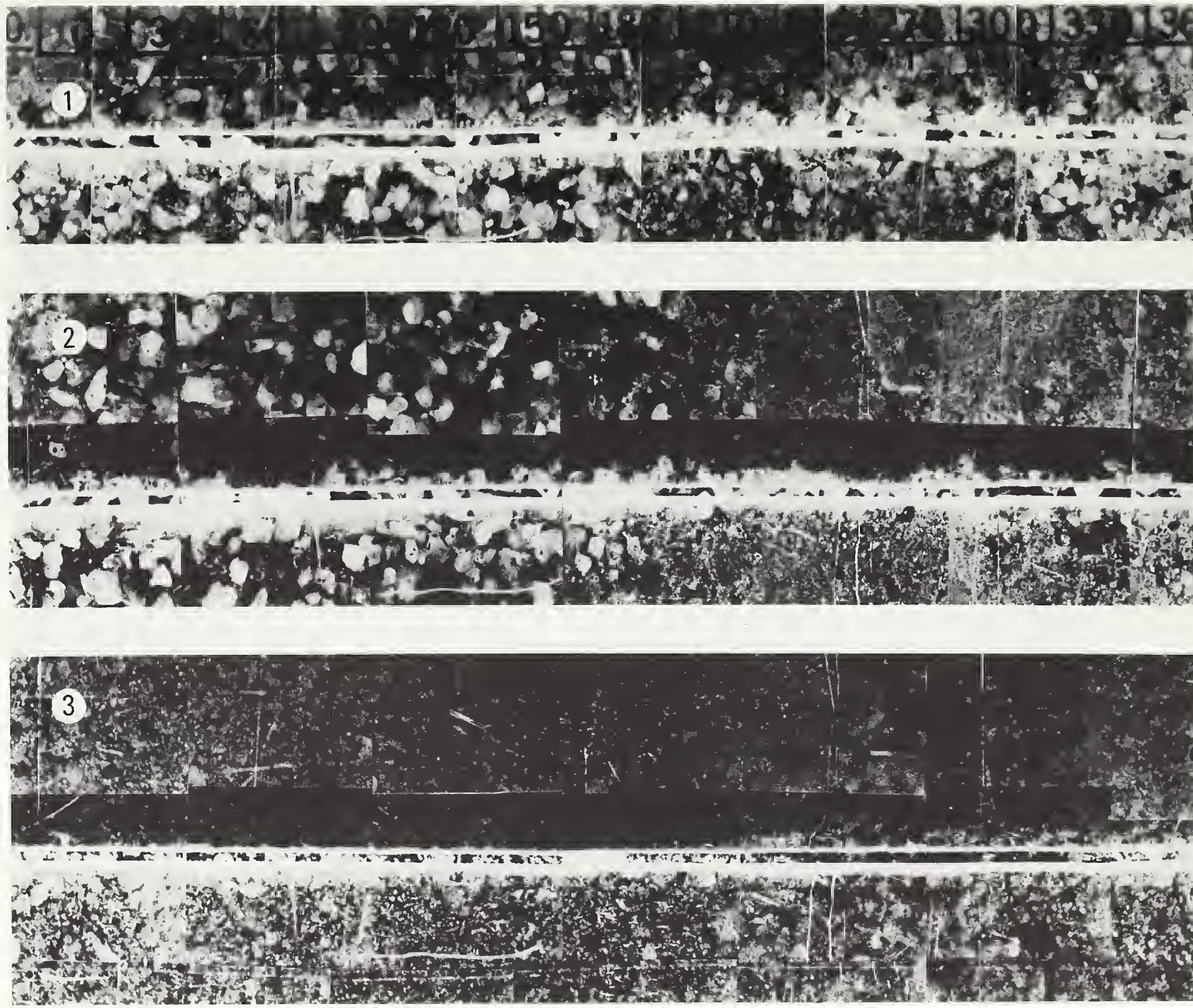

Figure 4.--Particle arrangement in and around the drain both after drainage with 5 and 20 percent fine material added and before drainage with the 20-percent treatments.

EFFECTIVENESS OF VARIOUS SAND AND GRAVEL SEPARATES FOR DRAIN ENVELOPES

By James N. Luthin[1]

INTRODUCTION

This study tested the effectiveness of various sand and gravel separates in gravel envelopes. Some design criteria that governmental agencies use for drain envelopes were developed for gravel packs around wells. Although flow around a well is similar to that around a drain, flow is much faster near a well, and the lower amount of gravel required allows the use of a more expensive type of gravel envelope. The carefully graded envelope that is possible around a well is too expensive for an on-farm drainage system. The study reported here tested various envelope materials under conditions simulating those in the vicinity of a subsurface drain line, such as a tile drain.

The movement of fine sands and silts into drains depends on several factors. For example, unduly wide cracks between drain pipes allow soil materials to move into the drain along with the drainage water. In irrigated areas, the backfill in the drainage trench is settled by adding water at the top of the trench. In some cases, such water will erode material from the backfill and carry it into the drains.

In a carefully installed drainage system with a properly settled backfill, the movement of fine sands and silts into the drain is postulated to be a result of upward moving water entering the bottom of the drain. Luthin et al.[2] described the mechanical forces involved in some detail.

A measure of the force exerted on the soil particles by upward moving water is the *hydraulic gradient*. When water moves from soil into atmosphere or into a drain, the hydraulic gradient at the interface is called the *exit gradient*. An exit gradient greater than 1.0 will lift sand particles. That is the *critical gradient*. As sand particles at the interface begin to separate from the soil mass, bulk density is decreased. The decrease in bulk density is called a *quick condition*. In the quick condition, the entire soil mass near the interface

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[1]Professor of Water Science and Civil Engineering, University of California, Davis.

[2]Luthin, J. N., G. S. Taylor, and C. Prieto. Exit gradients into subsurface drains. Hilgardia 39(15): 419-428.

loses its internal friction as the particles separate. The soil acts like a fluid and flows into the drain.

There are two possible ways of preventing a quick condition. One is to reduce the exit gradient below the critical value. A more practical solution, however, is to effectively increase the weight of the soil particles so that the value of the critical gradient is increased. That can be done by transferring the weight of the backfill material to the basic soil beneath the drain. That is the purpose of the envelope. It should be so constructed that the weight of the backfill is evenly transferred to all of the soil particles (larger than clay) at the interface between the basic soil and the drain. If the weight of the overburden is transferred to the soil, then the weight of the overburden must be used in calculating the critical gradient.

The experiments reported here measured the movement of soil into gravel envelopes of various sizes, with and without an external load corresponding to an overburden.

An additional reason for these experiments is that some drainage practitioners have recommended using gravel separates of a single size, such as pea gravel. Our experiments tested all single-sized separates for effectiveness in preventing fine sands and silts from moving through them.

Luthin et al. showed that the theoretical exit gradient could be as high as 13 under ponded soil conditions. The actual value will depend on drain diameter, its depth beneath the water table, and the distance from the drain to an impermeable layer; however, ponded soil conditions are unusual under field conditions. To obtain realistic values of the exit gradients, measurements were made in a sand-filled tank as described by Orhun and Luthin (this publication). A drain 10 cm in diameter was placed, as shown in Orhun and Luthin, with reservoirs at each end of the tank. Three cases were investigated with water levels in reservoirs of 107.5, 141.0, and 172 cm above the bottom of the tank. The center of the drain was at an elevation of 77 cm. Measurements were made by installing piezometers at 2-cm intervals on a vertical line beneath the drain. Measurements were made with an empty drain, a drain one-quarter full, and a drain one-half full. Since water height had negligible effects on the exit gradient, results are given only for the empty drain.

To relate the water-table heights to the field situation, let us assume a drain spacing in the field of 30.5 m (about 100 ft). Assuming an elliptically shaped water table, water-table heights at the midpoint between drains would be as follows:

Height of water above center of drain at 152 cm from drain	Calculated water-table height at midpoint for a drain spacing of 15.24 m (50 ft)	Exit gradient into drain
Centimeters	*Meters*	
95	2.2	4.0
64	1.5	2.1
30.5	0.7	1.5

It seems likely that the exit gradients encountered in the field will be less than 5 unless the soil surface is ponded.

Table 1 shows the size ranges of materials retained on different grading screens. It also shows particle-size distributions for four natural materials. The natural envelope materials were tested as envelopes against some of the separates obtained by sieving. This information is given in the footnotes to table 1.

TABLE 1.--*Size ranges of material separates obtained by sieving and particle-size distributions in percent composition by weight*

Screen No.	Size range (mm)	Imperial Valley Gravel	Coachella Valley Gravel	Imperial Valley No. 1 Gravel	Oso Flaco Dune sand
1/4	6.35	10.67	8.56	---	---
4	6.35 -4.699	4.78	6.39	---	---
7	4.699-2.794	8.66	21.10	0.46	---
10	2.794-2.00	6.34	15.32	5.96	---
20	2.00 -0.840	20.81	24.75	20.83	---
40	0.840-0.420	36.20	16.12	21.48	1.84
60	0.420-0.250	10.39	2.39	29.81	31.53
80	0.250-0.177	1.84	1.29	13.52	39.19
100	0.177-0.149	.64	.98	4.67	21.99
140	0.149-0.105	.31	.95	1.99	4.10
>140	0.105-0.00	.11	2.18	1.53	1.40
Sample size used (grams)		449.1	1,000.0	1,000.0	1,000.0

Coachella Valley Gravel

Tested with No. 100 sand as base material and did not fail at gradients in excess of 8.

Imperial Valley No. 1 Gravel

Tested with No. 80 and No. 100 sands and did not fail.

Imperial Valley Gravel

Tested with No. 80 and No. 100 sands and failed at an exit gradient of 6.66 while loaded. The fine sand in this envelope material boiled and moved out of the envelope.

Various combinations of particle-size separates were tried as envelopes. For example, an envelope made of 50 percent each of particles retained on the one-quarter and No. 10 screens was tested using Oso Flaco sand as a soil or base material. The envelope failed with and without a load. An envelope made of 20 percent each of particles retained on the one-quarter, 4, 7, 10 and 20 screens was tested with load against all the base materials used and performed well with all of them.

Table 2 shows how various soils and soil separates responded to four different envelope materials. The soils showed higher failure gradients than the soil separates. In some cases, addition of a load increased the failure gradient.

TABLE 2.--*Failure gradients for different base materials tested against four envelopes*

Base material	Void ratio (e)	Height of H_2O	Failure gradient	Volume of discharge: Before failure	Volume of discharge: After failure
		Centimeters		---*Cm*^{3}*/min*---	
Pea gravel envelope					
Oso Flaco:					
Sand		50.2	2.08	166	250
Do.		51.4	2.17	157	625
No. 40 sand		83.5	3.58	900	---
No. 60 sand		[1]54.1	<2	---	---
No. 60 sand		51.6	2.08	222	680
No. 80 sand		48.2	1.50	187	535
No. 100 sand		45.5	1.42	87	534
No. 100 sand[2]		44.4	---	---	---
No. 140 sand		44.7	1.42	65	400
Columbia sandy loam		[3]110	4.20	---	---
		[4]110	5.50	---	---
Hanford sandy loam		[5]110	8.00	---	---
		[5]110	8.60	---	---
Panoche loam		[5]110	6.30	---	---
		[5]110	6.20	---	---
No. 4 Gravel envelope					
Oso Flaco:					
Sand	0.5702	54.1	2.17	237	700
Do.	.5984	54.1	2.00	265	750
Sand + load	.6017	52.8	1.75	185	620
Do.	.5923	53.9	1.67	260	800
No. 60 sand	.6447	50.4	1.67	215	670
Do.	.6458	52.7	1.75	292	760
No. 60 sand + load	.6103	52.7	1.67	295	800
Do.	.6367	52.7	1.41	310	760
No. 80 sand	.6835	47.0	1.41	183	610
Do.	.6629	48.0	1.58	167	620
No. 80 sand + load	.6736	48.1	1.50	155	600
Do.	.6682	48.1	1.41	172	636
No. 100 sand	.6635	45.1	1.58	115	520
Do.	.6251	45.7	1.66	95	530
No. 100 sand +load	.5861	45.7	1.33	92	540
Do.	.6475	44.6	1.41	95	---
No. 140 sand	.5641	45.7	1.58	84	460
Do.	.5264	45.8	1.66	82	480
No. 140 sand + load	.5205	45.8	1.66	68	---
Do.	.5348	45.8	1.66	76	480
No. 40 sand[2]	.6154	80.5	3.33	850	---
No. 40 sand + load	.6532	85.5	2.50	980	---

See footnotes at end of table.

TABLE 2.--*Failure gradients for different base materials tested against four envelopes*--Continued

Base material	Void ratio (e)	Height of H_2O	Failure gradient	Volume of discharge	
				Before failure	After failure
		Centimeters		---*Cm*^{3}/*min*----	
No. 7 Gravel envelope					
Oso Flaco:					
Sand	0.5967	59.2	2.17	350	780
Do.	.6439	[2]56.0	2.66	242	---
Sand + load	.6183	59.1	2.33	380	700
Do.	.6056	63.2	2.00	350	880
No. 60 sand	.6315	59.0	2.66	355	870
Do.	.6936	56.9	2.16	385	800
No. 60 sand + load	.6642	55.1	1.58	345	736
Do.	.6254	60.0	2.48	405	960
No. 80 sand	.6615	50.8	1.83	340	660
Do.	.7038	50.4	1.91	240	650
No. 80 sand + load	.7141	49.3	1.75	200	600
Do.	.6747	50.7	1.33	235	660
No. 100 sand	.6124	47.1	1.58	140	530
Do.	.6403	47.1	1.92	145	1020
No. 100 sand + load	.6230	48.3	1.67	110	---
Do.	.6437	48.1	1.50	115	520
No. 140 sand	.5383	47.2	1.67	75	470
Do.	.5480	47.0	1.75	90	500
No. 140 sand + load	.5473	47.1	1.41	75	---
Do.	.5835	47.0	1.83	87	480
No. 40 sand	.6420	[2]89.5	2.67	980	---
No. 40 sand + load	.6601	105.2	2.83	1000+	---
Envelope mixture 25 percent (1/4 inch, No. 4, No. 7, No. 10)					
Oso Flaco:					
Sand	.636	72.1	3.33	440	
Do.	.592	62.7	2.83	280	
Sand + load	.597	59.0	2.66	250	
Do.	.667	56.1	3.33	260	
No. 40 sand	.621	100.0	4.66	1000	
Do.	.696	100.0	3.50	1160	
No. 40 sand + load	.621	91.5	4.41	1000	
Do.	.598	100.0	5.00	1000	
No. 60 sand	.675	48.2	2.50	210	
Do.	.662	76.5	4.66	480	
No. 60 sand + load	.620	66.4	4.08	310	
Do.	.605	60.6	2.58	330	
No. 80 sand	.702	51.5	2.41	200	
Do.	.677	47.3	2.50	160	

See footnotes at end of table.

TABLE 2.--*Failure gradients for different base materials tested against four envelopes*--Continued

Base material	Void ratio (e)	Height of H_2O	Failure gradient	Volume of discharge: Before failure	Volume of discharge: After failure
		Centimeters		---*Cm³/min*---	
Envelope mixture 25 percent (1/4 inch, No. 4, No. 7, No. 10)					
Oso Flaco:					
No. 80 sand + load	0.636	52.0	1.83	200	
Do.	.729	46.2	1.83	160	
No. 100 sand	.653	47.4	2.33	120	
Do.	.685	49.5	1.83	130	
No. 100 sand + load	.655	45.2	1.91	100	
Do.	.688	44.7	2.00	110	
No. 140 sand	.550	43.5	2.50	80	
Do.	.487	43.0	1.50	70	
No. 140 sand + load	.597	45.6	1.00	75	
Do.	.568	44.1	1.83	65	

[1]Column immediately developed a quick condition.
[2]Column was pushed out of plastic cylinder by force of water. Load is 2970.8 g.
[3]Soil penetrated filter at distance of 0.6 cm.
[4]Soil penetrated filter at distance of 1.3 cm.
[5]Soil did not penetrate filter.

Table 3 shows how three natural envelope materials responded to single-size separates. The natural envelope materials could support higher gradients than the envelopes made by combining sieved materials.

TABLE 3.--*Natural envelope material test results*

Envelope material	Void ratio (e)	Height of H_2O	Gradients	Volume of discharge
		Centimeters		*Cm³/min*
Coachella Valley:				
No. 100 sand	0.658	[1]74.9	---	240
No. 100 sand + load	.698	100.0	8.41	440
Imperial Valley:				
No. 100 sand	.758	[1]48.5	---	220
No. 100 sand + load	.667	100.0	8.16	460
Imperial Valley No. 1:				
No. 80 sand	.675	[1]46.5	---	90
No. 80 sand + load	.754	89.4	6.66	560

[1]Sand was lifted out of column by force of water.

Table 4 shows the response of three soils to two envelope materials constructed by combining sieved materials. In most cases, failure did not occur with gradients as high as 10.

TABLE 4.--*Tests of several soils against two constructed envelope materials*

Envelope material	Soil	Void ratio	Exit gradient soil first moves into envelope
1/2 (No. 10, No. 20)	Columbia sandy loam	1.160	7.5
		1.140	7.8
	Hanford sandy loam	.768	([1])
		.815	([1])
	Panoche loam	.733	([1])
		.889	([1])
1/3 (No. 10, No. 20, No. 40)	Columbia sandy loam	1.115	([1])
		1.092	([1])
	Hanford sandy loam	.769	([1])
		.854	([1])
	Panoche loam	.709	([1])
		.734	([1])

[1]At exit gradients in excess of 10, soil did not move into the envelope.

EXPERIMENTAL PROCEDURE

Measurements were made with the apparatus shown in figure 1. Note that water flows from the bottom to the top. A 3.7-cm layer of No. 10 coarse sand was placed at the bottom of the column to eliminate any turbulence. A copper screen was placed on the No. 10 sand. The material corresponding to the basic soil was then placed on the screen. The basic soil was added in small lifts and tamped with a one-inch plastic rod. About 600 g of basic soil was added to a layer about 8 cm thick. Envelope material was placed on the basic soil without tamping. The thickness of the envelope was about 5-6 cm and weighed 405 g. To simulate the load of the overburden, a perforated plastic disk was placed on the envelope material and weighted with lead weights.

The tests were performed by adding distilled de-aired water so that it flowed upward through the envelope material and emerged at the top of the column. Hydraulic head was gradually increased by raising the water reservoir 1 to 2 cm at a time. Piezometer pressures were measured with a transducer. Each test was run in duplicate. A series of tests was run with a load of 3042.8 g added to the envelope material. Measurements were made of the volume of discharge for each successive height of the water reservoir. Measurements were also made at the moment when the sand first started to boil, when the sand first penetrated the envelope material, and when the sand had completely moved through the envelope. If the sand had not penetrated the envelope material by the time the reservoir level reached 100 cm, the test was concluded. The exit gradients varied but were generally greater than 5. The reservoir level is measured from

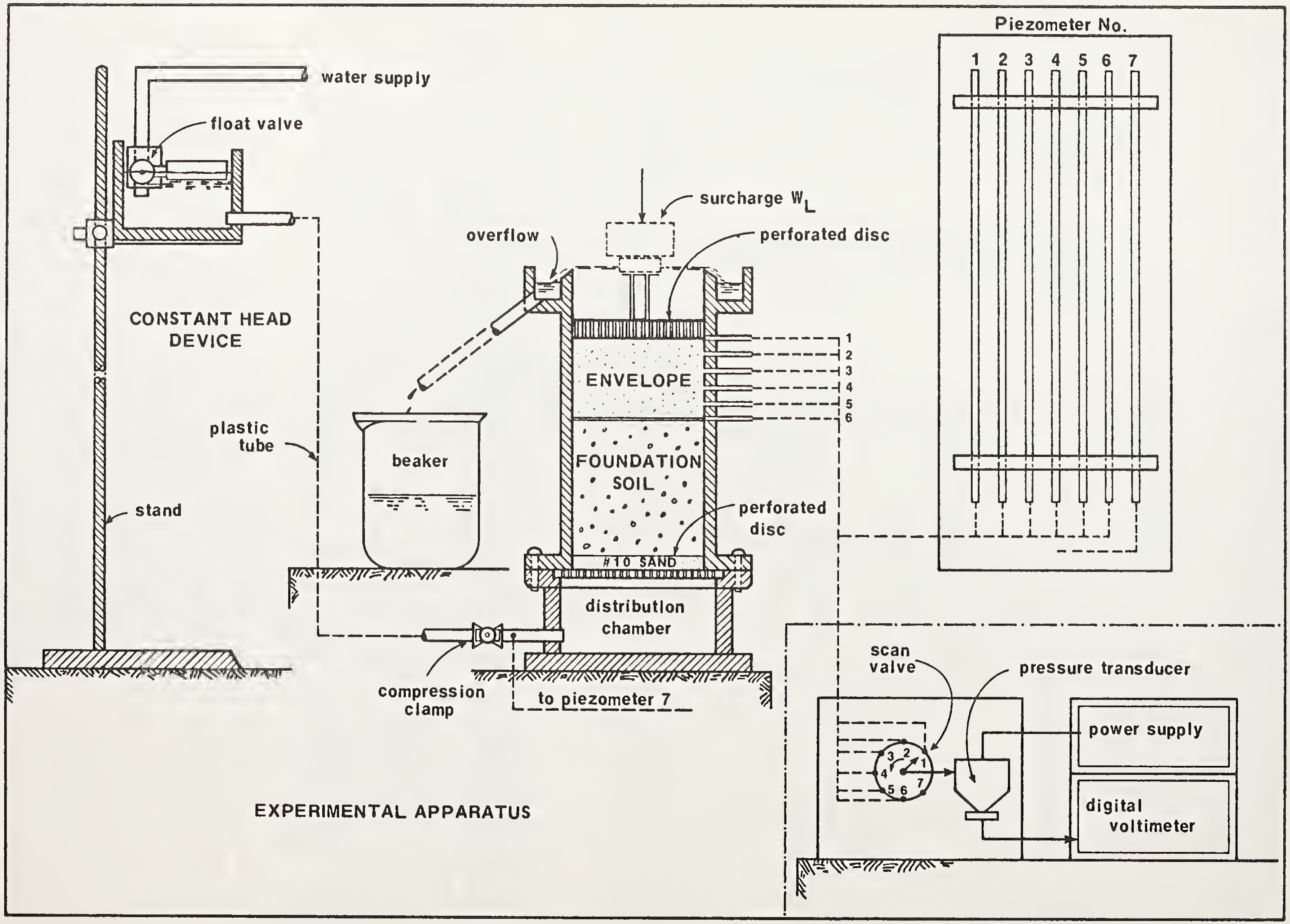

Figure 1.--Experimental apparatus.

the top of the laboratory table. The distance from the laboratory table to the bottom of the base material is 12.9 cm. Therefore, the pressure head at the bottom of the base material is 87.1 cm when reservoir height is 100 cm.

DISCUSSION

Several factors influence the effectiveness of an envelope, and not all were considered. Some of these other factors are indicated below.

a. Bridging: The bridging effect due to removal of smaller particles was not considered. The effectiveness of an envelope can be increased subtantially by bridging.

b. Angularity of envelope materials: The angularity of envelope materials also determines their effectiveness. Interlocking will reduce the possibility of particle movement. Most of the separates used as envelope material in our tests were rounded materials. Actual envelope from Coachella and Imperial Valleys were more angular, which may have increased their effectiveness.

c. Improvement of envelope by particle movement: The effectiveness of an envelope is often increased by the movement of particles from the base material into the envelope. The particles lodge in the pores of the envelope, decreasing their size and preventing further movement of base material.

d. Critical gradient, failure gradient: The critical gradient for a soil-air interface is about 1 for the materials tested. The weight of the envelope material increases the critical gradient to about 6. The failure gradients ranged from about 1.5 to 3.5, indicating that in almost every case the envelope material was at least partially effective. Loading the envelope increased the critical gradient to more than 6.

An envelope was considered satisfactory if it did not fail at an exit gradient of about 8 while loaded with the lead weights.

The failure gradient is the gradient at which the envelope failed. Some basic soil material migrates into the envelope before failure. The envelope is not considered "failed," however, until basic soil particles of the size of fine sand move through the envelope. At this time, the envelope starts to settle into the soil and merges with it.

CONCLUSIONS

Although no specific criterion is developed for the design of an envelope, some conclusions can be drawn from the results given here.

1. Single-sized separates, such as pea gravel, are not effective as envelope material in preventing fine sands and silts from moving into drains. They may serve as good bedding material. Also, they may improve flow into the drains by increasing conductivity adjacent to the drain.

2. Material smaller than No. 60 should be excluded from the envelope since material that small will move into the drain line.

3. A good envelope should contain appreciable amounts of No. 20 sand and some No. 40 and No. 10.

4. Envelope effectiveness is decreased by the larger-size fraction of gravel.

ACKNOWLEDGMENT

The experiments reported were performed by A. Haig, R. Lee, T. Howard, and S. Chan. The work was supported in part by the Office of Water Resources Research, "Drainage Design as Influenced by Conditions in the Vicinity of the Drain Line," W-212, OWRR Annual Allotment Funds.

TESTS OF SPUN-BONDED NYLON FABRIC AS AN ENVELOPE MATERIAL

By Akin Orhun and James N. Luthin[1]

A common synthetic envelope material for perforated plastic drain pipe is a nylon-screen covering. The nylon screen is a random-fiber unwoven material designed to prevent sand particles from entering the drain. On the other hand, the holes in the screen are large enough to permit fines (clay and silt) to pass.

The limited tests described below were to determine the effectiveness of spun-bonded nylon fabric material as a drain envelope. Its suitability must be tested under field conditions. No recommendation for or against the material is implied here.

The dimensions of the sand tank where the Drainguard experiments were carried out were 10-½ ft wide by 6 ft high by 3 ft deep (306 cm wide by 183 cm high by 91 cm deep). The tank was filled with Oso Flaco Dune Sand, with characteristics as reported in this publication under "Effectiveness of Various Sand and Gravel Separates for Drain Envelopes." Water is supplied to the tank through vertical gravel beds at both sides having a width of 3 inches (7.6 cm) each. The locations and the general arrangement of piezometers are shown in figure 1, following the tabular material. The origin of the Cartesian coordinate system used for the tank is at the bottom and along its symmetry axis. The coordinates of the piezometers are presented in this report. The soil surface is about 5 ft 10 inches (177.8 cm) above the bottom of the tank. Two manometer boards are used for measuring the hydraulic heads. Piezometer columns 1 through 7 are connected to the left manometer board, and columns 8 through 13 are connected to the right. The zero reading of the left manometer board corresponds to Y = 4.7 cm of the tank. Thus, to obtain hydraulic heads in terms of the tank's coordinate system, 4.7 cm of the head difference should be added to the left manometer-board readings. Similarly, 4.8 cm should be added to the right manometer-board readings. Discarded in evaluating the manometer readings were the hydraulic heads reported by piezometers observed to have a slight amount of soil moisture tension, even though they can give reliable results under small negative pressures.

The equipotentials shown in figures 2 to 5 are in percentages of maximum potential drop. The flow rates were measured volumetrically in a period of 2 min.

The following pages give the results of four experiments with three different maximum water table heights. The water tables calculated for each case and those given by Luthin and Haig[2] are drawn together with the calculated equipoten-

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[2]Luthin, J. N., and A. Haig. Some factors affecting flow into drainpipes. Hilgardia 41(10). 1972.

tials. The measured flow rates are compared with the flow rates reported by Luthin and Haig for a completely perforated pipe having the same diameter as the Drainguard pipe. Their measurements were made in the same tank.

The measured water table heights for almost all of the experiments are lower than those reported by Luthin and Haig for a drain diameter of 10 cm.

Throughout the experiments, the sand that had filtered into the drain was observed qualitatively. The fiber glass filter was satisfactory in general, although a small amount of sand filtered in during the first experiment, which had the highest exit gradient.

TABLE 1.--*The measured and reported flow rates*

Water level in reservoir	Measured flow rates	Reported (Luthin and Haig) flow rates
	Cm^3/sec	*Cm^3/sec*
Level A (CE272 Class)	183.55	186.2
Level A	180.83	186.2
Level B	103.80	119.3
Level C	45.36	59.2

Coordinates of the Piezometer Locations

Column	X coordinates			Row	Y coordinates		
	Feet	*Inches*	*Centimeters*		*Feet*	*Inches*	*Centimeters*
1	- 5	0	- 152.40	A	5	6	167.64
2	- 4	0	- 121.92	B	5	0	152.40
3	- 3	0	- 91.44	C	4	6	137.16
4	- 2	0	- 60.96	D	4	0	121.92
5	- 1	0	- 30.48	E	3	6	106.68
6	-	6	- 15.24	F	3	0	91.44
7	+	0	0	G	2	6	76.20
8	∓	6	+ 15.24	H	2	0	60.96
9	+ 1	0	+ 30.48	H'	1	10.5	57.15
10	+ 2	0	+ 60.96	I'	1	9	53.34
11	+ 3	0	+ 91.44	I	1	6	45.72
12	+ 4	0	+ 121.92	J	1	0	30.48
13	+ 5	0	+ 152.40	K	---	6	15.24
				L	---	2	5.08

Soil surface elevations:
Y = 5 ft 10 inches
= 177.80 cm
Tank width:
W = 3 ft
= 91.44 cm

SMALL SAND TANKS

Drain diameter:	4.5 inches	Time:	11:15 a.m.
Outflow rate:	11.013 L/min	Date:	March 5, 1973
State:	Steady, free water	Temperature:	22°C
Drain type:	PVC, corrugated	Reader:	CE 272 class

Position	Total head of water	Pressure	Position	Total head of water	Pressure
	----Centimeters------			-----Centimeters-----	
1 A	171.0	3.36	13 A	171.5	3.86
1 B	171.0	18.6	13 B	170.1	17.7
1 C	170.7	33.54	13 C	171.7	34.54
1 D	170.8	48.88	13 D	172.3	50.38
1 E	172.1	65.42	13 E	172.4	65.72
1 F	172.1	80.66	13 F	173.9	82.45
1 G	173.2	97.0	13 G	174.0	97.80
1 H	173.5	112.54	13 H	174.6	113.64
1 I	173.8	128.08	13 I	175.4	129.68
1 J	175.2	144.72	13 J	175.7	145.22
1 K	175.1	158.86	13 K	174.9	159.66
1 L	---	---	13 L	[1]175.7	170.62
2 B	162.8	10.4	12 B	164.1	11.7
2 D	163.2	41.28	12 D	164.7	42.78
2 F	163.3	71.86	12 F	164.6	73.16
2 H	163.6	102.6	12 H	166.1	105.14
2 J	164.5	134.02	12 J	166.4	135.92
2 L	165.0	159.92	12 L	167.8	162.72
3 A	[2]150.0	---	11 A	[2]164.0	---
3 C	154.1	16.94	11 C	153.5	16.34
3 E	154.2	42.52	11 E	151.9	45.22
3 G	154.4	78.2	11 G	154.2	78.0
3 I	155.2	109.48	11 I	155.8	110.08
3 K	155.0	139.76	11 K	157.3	142.06
3 L	155.3	150.22	11 L	157.4	152.32
4 B	[1]144.8	---	10 B	[1]146.9	---
4 D	144.0	22.08	10 D	145.7	23.78
4 F	144.3	52.86	10 F	145.5	54.06
4 H	144.9	83.94	10 H	147.5	86.54
4 J	147.4	116.92	10 J	150.0	119.52
4 L	147.8	147.72	10 L	151.5	146.42
5 A	[2]167.8	---	9 A	[2]167.8	---
5 B	[2]137.3	---	9 B	[2]139.1	---
5 C	[2]135.6	---	9 C	[2]137.0	---
5 D	134.7	12.78	9 D	134.7	12.78
5 E	131.0	24.32	9 E	132.6	25.92
5 F	128.9	37.46	9 F	128.0	35.56
5 G	125.5	49.30	9 G	131.0	54.80
5 H	130.5	69.54	9 H	133.6	72.64

See footnotes at end of table.

Position	Total head of water	Pressure	Position	Total head of water	Pressure
	----*Centimeters*-----			----*Centimeters*-----	
5 I	136.5	90.78	9 I	139.1	93.38
5 J	138.8	108.32	9 J	141.0	110.52
5 K	143.0	127.76	9 K	143.2	127.96
5 L	142.9	137.82	9 L	145.2	140.12
6 A	[2]165.6	---	8 A	---	---
6 B	[2]138.1	---	8 B	147.7	---
6 C	[2]132.9	---	8 C	134.6	---
6 D	129.5	7.58	8 D	130.7	8.78
6 E	123.8	17.12	8 E	125.5	18.82
6 F	128.0	36.56	8 F	118.4	26.96
6 G	101.3	25.10	8 G	104.2	28.00
6 H	120.4	59.44	8 L	125.2	64.24
6 I	132.6	86.88	8 I	130.5	84.78
6 J	135.8	105.32	8 J	136.2	105.72
6 K	140.5	125.26	8 K	141.1	125.86
6 L	140.6	135.52	8 L	141.6	136.52
7 A	[2]128.2	---			
7 B	[2]136.1	---			
7 C	[2]132.8	---			
7 E	[2]123.8	17.12			
7 F	100.0	8.56			
7 H	116.9	55.94			
7 H'	103.6	46.45			
7 I					
7 I'	135.7	82.36			
7 K	140.2	124.96			

[1]Maximum hydraulic head to be used in calculating percent potentials.
[2]Tension exists at the piezometer location. Discard the data.

Drain diameter: 4.5 inches
Outflow rate: 11.013 L/min.
State: Free water surface
Drain type: PVC, corrugated

Time: 11:15 a.m.
Date: March 5, 1973
Temperature: 22°C
Reader: CE 272 Class

Note: Water level in drain was 67.7 cm. Add 4.5 cm to all readings reported below to convert them to the coordinate system of the tank

Position	Total head of water	Remarks	Position	Total head of water	Remarks
	Centimeters	*Percent* ϕ		*Centimeters*	*Percent* ϕ
1 A	166.5	95.45	13 A	167.0	95.94
1 B	166.5	95.45	13 B	165.6	94.59
1 C	166.2	95.17	13 C	167.2	96.14
1 D	166.3	95.19	13 D	167.8	96.71

Position	Total head of water	Remarks	Position	Total head of water	Remarks
	Centimeters	*Percent* ϕ		*Centimeters*	*Percent* ϕ
1 E	167.6	95.26	13 E	167.9	96.81
1 F	167.6	95.26	13 F	169.4	98.26
1 G	168.7	97.58	13 G	169.5	98.36
1 H	169.0	97.87	13 H	170.1	98.94
1 I	169.3	98.16	13 I	170.9	99.71
1 J	170.7	99.51	13 J	171.2	100.0
1 K	169.6	98.45	13 K	170.4	99.23
1 L	---	---	13 L	171.2	100.0
2 B	158.3	87.53	12 B	159.6	88.79
2 D	158.7	87.92	12 D	160.2	89.37
2 F	158.8	88.01	12 F	160.1	89.27
2 H	159.1	88.30	12 H	161.6	90.72
2 J	160.0	89.17	12 J	161.9	91.01
2 L	160.5	89.66	12 L	163.3	92.36
3 A	145.5	---	11 A	159.5	---
3 C	149.6	79.13	11 C	149.0	78.55
3 E	149.7	79.22	11 E	147.4	77.00
3 G	149.9	79.42	11 G	149.7	79.22
3 I	150.7	80.19	11 I	151.3	80.77
3 K	150.5	80.00	11 K	152.8	82.22
3 L	150.8	80.28	11 L	152.9	82.31
4 B	140.3	---	10 B	142.4	---
4 D	139.5	69.37	10 D	141.2	71.01
4 F	139.8	69.66	10 F	141.0	70.82
4 H	140.4	70.24	10 H	143.0	72.75
4 J	142.9	72.65	10 J	145.5	75.16
4 L	143.3	73.04	10 L	146.8	76.42
5 A	163.3	---	9 A	163.3	---
5 B	132.8	---	9 B	134.6	---
5 C	131.1	---	9 C	132.5	---
5 D	130.2	60.38	9 D	130.2	60.38
5 E	126.5	56.81	9 E	128.1	58.35
5 F	124.4	54.78	9 F	123.5	53.91
5 G	121.0	51.49	9 G	126.5	56.81
5 H	126.0	56.32	9 H	129.1	59.32
5 I	132.0	62.12	9 I	134.6	64.63
5 J	134.3	64.34	9 J	136.5	66.47
5 K	138.5	68.40	9 K	138.7	68.59
5 L	138.4	68.30	9 L	140.7	70.53
6 A	161.1	---	8 A	---	---
6 B	133.6	---	8 B	143.2	---
6 C	128.4	---	8 C	130.1	---
6 D	125.0	55.36	8 D	126.2	56.52
6 E	119.3	49.85	8 E	121.0	51.49
6 F	123.5	53.91	8 F	113.9	44.63
6 G	96.8	28.11	8 G	99.7	30.91
6 H	115.9	46.57	8 L	120.7	51.20
6 I	128.1	58.35	8 I	126.0	56.32

Position	Total head of water	Remarks	Position	Total head of water	Remarks
	Centimeters	*Percent* ϕ		*Centimeters*	*Percent* ϕ
6 J	131.3	61.44	8 J	131.7	61.83
6 K	136.0	65.99	8 K	136.6	66.57
6 L	136.1	66.08	8 L	137.1	67.05
7 A	123.7	---			
7 B	131.6	---			
7 C	128.3	---			
7 E	119.3	49.86			
7 F	95.5	26.85			
7 H	112.4	43.18			
7 H'	99.1	30.33			
7 I	---	---			
7 I'	131.2	61.35			
7 K	135.7	65.70			

Comments: Water-table elevations are as follows:

Column	*Elevation (cm)*	*Column*	*Elevation (cm)*
1	170.5	7	123.8
2	162.9	8	135.0
3	154.1	9	138.0
4	144.1	10	144.9
5	138.2	11	153.8
6	133.8	12	164.0
		13	171.0

Drain diameter: 4.5 inches
Outflow rate: 10.85 L/min
State: Steady, free water surface
Drain type: PVC, corrugated fiber glass

Time: 9:30 a.m.
Date: March 6, 1973
Temperature: 22°C
Reader: Akin Orhun

Add 4.7 cm. to the left manometer readings to get the total head

Add 4.8 cm to the right manometer readings to get the total head

Position	Total head of water	Manometer reading	Position	Total head of water	Manometer reading
	-----*Centimeters*-----			-----*Centimeters*-----	
1 A	170.9	166.2	13 A	171.5	166.7
1 B	171.0	166.3	13 B	170.0	165.2
1 C	170.6	165.9	13 C	172.1	167.3
1 D	170.2	165.5	13 D	172.6	167.8
1 E	171.7	167.0	13 E	172.6	167.8
1 F	171.9	167.2	13 F	174.2	169.4
1 G	172.8	168.1	13 G	174.5	169.7
1 H	172.4	167.7	13 H	174.9	170.1
1 I	173.5	168.8	13 I	175.7	170.9

Position	Total head of water	Manometer reading	Position	Total head of water	Manometer reading
	-----Centimeters-----			-----Centimeters-----	
1 J	175.4	170.7	13 J	[1]175.8	171.0
1 K	174.6	169.9	13 K	174.9	170.1
1 L	---	---	13 L	174.9	170.1
2 B	162.4	157.7	12 B	164.4	159.6
2 D	162.7	158.0	12 D	164.9	160.1
2 F	163.1	158.4	12 F	164.9	160.1
2 H	163.1	158.4	12 H	166.5	161.7
2 J	164.2	159.5	12 J	166.4	161.6
2 L	164.3	159.6	12 L	167.5	162.7
3 A	[2]152.3	147.6	11 A	[2]164.6	159.8
3 C	153.8	149.1	11 C	153.6	148.8
3 E	153.7	149.0	11 E	152.1	147.3
3 G	154.0	149.3	11 G	154.4	149.6
3 I	154.7	150.0	11 I	155.9	151.1
3 K	154.4	149.7	11 K	157.2	152.4
3 L	154.6	149.9	11 L	157.5	152.7
4 B	[2]150.1	145.4	10 B	[2]146.1	141.3
4 D	143.4	138.7	10 D	145.5	140.7
4 F	143.7	139.0	10 F	145.2	140.4
4 H	144.4	139.7	10 H	147.2	142.4
4 J	146.9	142.2	10 J	149.9	145.1
4 L	147.4	142.7	10 L	151.0	146.2
5 A	[2]168.1	163.4	9 A	[2]166.4	161.6
5 B	[2]137.9	133.2	9 B	[2]140.5	135.7
5 C	[2]134.8	130.1	9 C	[2]134.7	129.9
5 D	134.0	129.3	9 D	134.3	129.5
5 E	130.7	126.0	9 E	132.4	127.6
5 F	128.2	123.5	9 F	127.9	123.1
5 G	125.6	120.9	9 G	130.8	126.0
5 H	129.6	124.9	9 H	133.2	128.4
5 I	135.7	131.0	9 I	139.0	134.2
5 J	138.4	133.7	9 J	141.3	136.5
5 K	142.1	137.4	9 K	143.2	138.4
5 L	142.0	137.3	9 L	144.8	140.0
6 A	165.9	161.2	8 A	144.5	139.7
6 B	142.3	137.6	8 B	133.3	128.5
6 C	131.3	126.6	8 C	130.4	125.6
6 D	128.1	123.4	8 D	125.6	120.8
6 E	132.5	118.8	8 E	118.2	113.4
6 F	114.7	110.0	8 F	105.4	100.6
6 G	101.2	96.5	8 G	127.0	122.2
6 H	120.0	115.3	8 H	132.2	127.4
6 I	132.4	127.7	8 I	136.2	131.4
6 J	135.2	130.5	8 J	---	---
6 K	139.8	135.1	8 K	---	---
6 L	140.1	135.4	8 L	---	---
7 A	[2]167.3	162.6			
7 B	[2]144.5	139.8			

Position	Total head of water	Manometer reading	Position	Total head of water	Manometer reading
	-----Centimeters-----			-----Centimeters-----	
7 C	[2]131.4	126.7			
7 E	118.5	123.2			
7 F	98.9	94.2			
7 H	122.8	118.1			
7 H'	117.8	113.1			
7 I	---	---			
7 I'	---	---			
7 K	139.6	134.9			
Drain	[3]73.5	68.8			

[1]Maximum potential.
[2]Discarded data because of tension at the piezometer location.
[3]Minimum potential.

Drain diameter:	4.5 inches	Time:	9:30 a.m.
Outflow rate:	10.85 L/min	Date:	March 6, 1973
State:	Steady, free water surface	Temperature:	22°C
Drain type:	PVC, corrugated, fiber glass	Reader:	Akin Orhun

Position	Total head	Pressure of H_2O	Position	Total head	Pressure of H_2O
	Percent	*Centimeters*		*Percent*	*Centimeters*
1 A	95.21	3.26	13 A	95.79	3.86
1 B	95.30	18.6	13 B	94.33	17.6
1 C	94.91	33.44	13 C	96.38	34.94
1 D	94.52	48.28	13 D	96.87	50.65
1 E	95.99	65.02	13 E	96.87	65.92
1 F	96.18	80.46	13 F	98.43	82.76
1 G	97.06	96.60	13 G	98.72	98.30
1 H	96.67	111.44	13 H	99.12	113.94
1 I	97.76	127.78	13 I	99.90	129.98
1 J	99.60	144.99	13 J	100.00	145.32
1 K	98.82	159.36	13 K	99.12	159.66
1 L	---	---	13 L	99.12	169.82
2 B	86.90	10.0	12 B	88.85	12.0
2 D	87.19	40.78	12 D	89.34	42.98
2 F	87.58	71.66	12 F	89.34	73.46
2 H	87.58	102.14	12 H	90.90	105.54
2 J	88.66	133.72	12 J	90.81	135.92
2 L	88.75	159.22	12 L	91.88	162.42
3 A	[1]77.02	-15.34	11 A	[1]89.05	-3.04
3 C	78.49	16.64	11 C	78.29	16.44
3 E	78.39	47.02	11 E	76.83	45.42
3 G	78.69	77.80	11 G	79.08	78.20

Position	Total head	Pressure of H_2O	Position	Total head	Pressure of H_2O
	Percent	*Centimeters*		*Percent*	*Centimeters*
3 I	79.37	108.98	11 I	80.54	110.18
3 K	79.08	139.16	11 K	80.05	141.96
3 L	79.27	149.52	11 L	82.11	152.42
4 B	[1]74.87	-2.3	10 B	[1]70.96	-6.3
4 D	68.32	21.48	10 D	70.38	23.58
4 F	68.62	52.56	10 F	70.08	53.76
4 H	69.30	83.44	10 H	72.04	86.24
4 J	71.74	116.42	10 J	74.68	119.42
4 L	72.23	142.32	10 L	75.75	145.92
5 A	[1]92.47	0.46	9 A	[1]90.81	-1.24
5 B	[1]62.95	-14.5	9 B	[1]65.49	-11.9
5 C	[1]59.92	-2.36	9 C	[1]59.82	-2.46
5 D	59.13	12.08	9 D	59.43	12.38
5 E	55.91	24.02	9 E	57.57	25.72
5 F	53.47	36.76	9 F	53.17	36.46
5 G	50.92	49.40	9 G	56.01	54.60
5 H	54.83	68.64	9 H	58.35	72.24
5 I	60.80	89.98	9 I	65.02	93.28
5 J	63.44	107.92	9 J	66.27	110.82
5 K	67.05	126.86	9 K	68.13	127.96
5 L	66.95	136.92	9 L	69.69	139.72
6 A	[1]90.32	-1.74	8 A	---	---
6 B	[1]73.50	-10.1	8 B	[1]69.40	-7.9
6 C	[1]56.50	-5.86	8 C	[1]58.45	-3.86
6 D	53.37	6.18	8 D	55.62	8.48
6 E	48.87	16.82	8 E	50.92	18.92
6 F	40.27	23.26	8 F	43.69	26.76
6 G	27.07	25.00	8 G	31.18	29.20
6 H	45.45	59.04	8 H	52.29	66.04
6 I	57.57	86.68	8 I	57.38	86.48
6 J	60.31	104.72	8 J	61.29	105.72
6 K	64.80	124.56	8 K	---	---
6 L	65.10	135.02	8 L	---	---
7 A	[1]91.69	-0.34			
7 B	[1]69.40	-7.9			
7 C	[1]56.59	-5.76			
7 E	43.98	11.82			
7 F	24.82	7.46			
7 H	48.19	61.84			
7 H'	43.30	60.65			
7 I	---	---			
7 I'	---	---			
7 K	64.61	124.36			

[1]Discarded data because of tension at the piezometer location.

Comments: Water-table elevations are as follows:

Column	Water table (cm)	Column	Water table (cm)
1	170.9	7	130.4
2	162.4	8	130.4
3	153.8	9	134.3
4	143.4	10	145.5
5	134.0	11	153.6
6	128.1	12	164.4
		13	171.5

Drain diameter:	4.5 inches	Time:	2:15 p.m.
Outflow rate:	6.23 L/min	Date:	March 9, 1973
State:	Steady, free-water surface	Temperature:	21.6°C
Drain type:	PVC, corrugated, fiber glass	Reader:	Akin Orhun

Position	Total head of water	Manometer reading	Position	Total head of water	Manometer reading
	-----*Centimeters*-----			-----*Centimeters*-----	
1 A	[1]170.4	165.7	13 A	([1])	---
1 B	[1]150.6	145.9	13 B	[1]133.4	128.6
1 C	[1]133.3	128.6	13 C	[1]133.6	131.8
1 D	134.9	130.2	13 D	137.3	132.5
1 E	135.5	130.8	13 E	137.0	132.2
1 F	135.3	130.6	13 F	140.5	135.7
1 G	135.5	130.8	13 G	137.7	132.9
1 H	135.2	130.5	13 H	137.8	133.0
1 I	135.8	131.1	13 I	138.1	133.3
1 J	136.4	131.7	13 J	137.5	132.7
1 K	135.4	130.7	13 K	136.5	131.7
1 L	---	---	13 L	[2]139.4	134.6
2 B	[1]129.4	124.7	12 B	---	---
2 D	129.2	124.5	12 D	131.5	126.7
2 F	129.1	124.4	12 F	131.4	126.6
2 H	129.1	124.4	12 H	131.9	127.1
2 J	129.6	124.9	12 J	131.5	126.7
2 L	129.7	125.0	12 L	132.1	127.3
3 A	[1]156.1	151.4	11 A	---	---
3 C	[1]123.4	118.7	11 C	124.0	119.2
3 E	123.0	118.3	11 E	123.2	118.4
3 G	123.3	118.6	11 G	123.8	119.0
3 I	123.45	118.76	11 I	124.7	119.9
3 K	123.3	118.6	11 K	125.6	120.8
3 L	123.5	118.8	11 L	125.8	121.0
4 B	[1]142.8	138.1	10 B	---	---
4 D	[1]115.4	110.7	10 D	[1]117.7	112.9
4 F	115.8	111.1	10 F	117.5	112.7
4 H	116.6	111.9	10 H	118.8	114.0
4 J	118.4	113.7	10 J	120.9	116.1
4 L	119.0	114.3	10 L	121.5	116.7
5 A	[1]168.6	163.9	9 A	---	---
5 B	[1]132.4	127.7	9 B	[1]134.4	129.6
5 C	[1]133.9	129.2	9 C	[1]109.3	104.5
5 D	[1]107.9	103.2	9 D	[1]108.7	103.9

Position	Total head of water	Manometer reading	Position	Total head of water	Manometer reading
	-----*Centimeters*-----			-----*Centimeters*-----	
5 E	[1]106.15	101.45	9 E	108.0	103.2
5 F	105.45	100.75	9 F	105.5	100.7
5 G	104.4	99.70	9 G	107.95	103.15
5 H	107.5	102.8	9 H	109.95	105.15
5 I	111.3	106.6	9 I	113.8	109.0
5 J	112.95	108.25	9 J	115.3	110.5
5 K	115.6	110.9	9 K	116.5	111.7
5 L	115.5	110.8	9 L	117.3	112.5
6 A	[1]161.2	156.5	8 A	---	---
6 B	[1]136.0	131.3	8 B	[1]134.8	130.0
6 C	[1]122.2	117.5	8 C	[1]139.1	134.3
6 D	[1]103.6	98.9	8 D	[1]104.8	100.0
6 E	[1]101.3	96.6	8 E	[1]102.8	98.0
6 F	97.1	92.4	8 F	99.2	94.4
6 G	90.3	85.6	8 G	92.6	87.8
6 H	101.6	96.9	8 L	---	---
6 I	108.5	103.8	8 I	109.0	104.2
6 J	111.2	106.5	8 J	112.5	107.7
6 K	113.9	109.2	8 K	---	---
6 L	114.3	109.6	8 L	105.0	100.2
7 A	---	---			
7 B	[1]133.2	128.5			
7 C	[1]122.4	117.7			
7 E	[1]110.5	105.8			
7 F	[1] 70.35	65.65			
7 H	100.1	95.4			
7 H'	101.8	97.1			
7 I	---	---			
7 I'	104.9	100.2			
7 K	113.8	109.1			
Drain	[3]72.2	67.5			

[1]Discarded data because of tension at the piezometer location.
[2]Maximum potential.
[3]Minimum potential.

Drain diameter:	4.5 inches	Time:	2:15 p.m.
Outflow rate:	6.23 L/min	Date:	March 9, 1973
State:	Steady, free water surface	Temperature:	21.6°C
Drain type:	PVC, corrugated fiber glass	Reader:	Akin Orhun

Position	Total head	Pressure of H_2O	Position	Total head	Pressure of H_2O
	Percent	*Centimeters*		*Percent*	*Centimeters*
1 A	[1]146.13	2.76	13 A	---	---
1 B	[1]116.66	-1.80	13 B	91.07	-19.00

Position	Total head	Pressure of H_2O	Position	Total head	Pressure of H_2O
	Percent	*Centimeters*		*Percent*	*Centimeters*
1 C	[1]90.92	-3.86	13 C	[1]95.83	-.56
1 D	93.30	12.98	13 D	96.87	15.00
1 E	94.19	28.82	13 E	96.42	30.32
1 F	93.89	43.86	13 F	101.63	49.06
1 G	94.19	59.30	13 G	97.47	61.5
1 H	93.75	74.24	13 H	97.61	76.84
1 I	94.64	90.08	13 I	98.06	92.38
1 J	95.53	105.92	13 J	97.17	107.02
1 K	94.04	120.16	13 K	95.68	121.26
1 L	---	---	13 L	100.00	134.32
2 B	[1]85.11	-23.00	12 B	---	---
2 D	84.82	7.28	12 D	88.24	9.58
2 F	84.67	37.66	12 F	88.09	39.96
2 H	84.67	68.14	12 H	88.83	70.94
2 J	85.41	99.12	12 J	88.24	101.02
2 L	85.56	124.62	12 L	89.13	127.02
3 A	[1]124.85	-11.54	11 A	---	---
3 C	[1]76.19	-13.76	11 C	[1]77.08	-13.16
3 E	75.59	16.32	11 E	75.89	16.52
3 G	76.04	47.10	11 G	76.78	47.60
3 I	76.26	77.73	11 I	78.12	78.93
3 K	76.04	108.06	11 K	79.46	110.36
3 L	76.33	118.42	11 L	79.76	120.72
4 B	[1]105.05	-9.6	10 B	---	---
4 D	[1]64.28	-6.52	10 D	[1]67.70	-4.22
4 F	64.88	24.36	10 F	67.41	26.06
4 H	66.07	55.64	10 H	69.34	57.84
4 J	68.75	87.92	10 J	72.47	90.42
4 L	69.64	113.92	10 L	73.36	116.42
5 A	[1]143.45	-6.44	9 A	---	---
5 B	89.58	-20.00	9 B	[1]92.25	-18.00
5 C	[1]91.81	-3.26	9 C	[1]55.20	-27.86
5 D	[1]53.12	-14.02	9 D	[1]54.31	-13.22
5 E	[1]50.52	-.53	9 E	53.27	1.32
5 F	49.47	14.01	9 F	49.55	14.06
5 G	47.91	28.20	9 G	53.19	31.75
5 H	52.52	46.54	9 H	56.17	48.99
5 I	58.18	65.58	9 I	61.90	69.08
5 J	60.63	82.47	9 J	64.13	84.82
5 K	64.58	100.36	9 K	65.92	101.26
5 L	64.43	110.42	9 L	67.11	112.22
6 A	[1]132.44	-6.44	8 A	---	---
6 B	[1]94.94	-16.40	8 B	[1]93.15	-17.6
6 C	[1]74.40	-14.96	8 C	[1]99.55	1.94
6 D	[1]46.72	-18.32	8 D	[1]48.51	-17.12
6 E	[1]43.30	-5.38	8 E	[1]45.54	-3.88
6 F	37.05	5.66	8 F	40.17	7.76
6 G	26.93	14.10	8 G	30.35	16.40

Position	Total head	Pressure of H_2O	Position	Total head	Pressure of H_2O
	Percent	*Centimeters*		*Percent*	*Centimeters*
6 H	43.75	40.64	8 H	---	---
6 I	54.01	62.78	8 I	54.76	63.28
6 J	58.03	80.72	8 J	59.97	82.02
6 K	62.05	98.66	8 K	---	---
6 L	62.64	109.22	8 L	48.80	99.92
7 A	---	---			
7 B	[1]90.77	-19.20			
7 C	[1]74.70	-14.76			
7 E	[1]56.99	3.82			
7 F	[1]-2.75	-21.09			
7 H	41.51	39.14			
7 H'	44.04	44.65			
7 I	---	---			
7 I'	48.66	51.56			
7 K	61.90	98.56			

Comments: Water-table elevations are as follows:

Column	*Water table (cm)*	*Column*	*Water table (cm)*
1	134.9	7	---
2	129.2	8	99.2
3	123.0	9	105.5
4	115.8	10	117.5
5	105.45	11	123.2
6	97.1	12	131.5
			137.3

Drain diameter: 4.5 inches
Outflow rate: 2.722 L/min
State: Steady, free water surface
Drain type: PVC, corrugated, fiber glass
Add 4.7 cm to the left manometer readings to get the total head

Time: 11:00 a.m.
Date: March 2, 1973
Temperature: 19.8°C
Reader: Akin Orhun
Add 4.8 cm to the right manometer readings to get the total head

Position	Total head of water	Manometer reading	Position	Total head of water	Manometer reading
	-----*Centimeters*-----			-----*Centimeters*-----	
1 A	---	---	13 A	---	---
1 B	---	---	13 B	---	---
1 C	---	---	13 C	---	---
1 D	[1]105.4	100.7	13 D	[1]106.4	101.6
1 E	106.7	102.0	13 E	107.3	102.5
1 F	106.8	102.1	13 F	---	---
1 G	107.1	102.4	13 G	108.0	103.2
1 H	106.6	101.9	13 H	108.1	103.3

Position	Total head of water	Manometer reading	Position	Total head of water	Manometer reading
	-----Centimeters-----			-----Centimeters-----	
1 I	107.1	102.4	13 I	[2]108.3	103.5
1 J	107.3	102.6	13 J	108.0	103.2
1 K	107.0	102.3	13 K	107.4	102.6
1 L	---	---	13 L	107.5	102.7
2 B	[1]103.3	98.6	12 B	---	---
2 D	103.2	98.5	12 D	[1]104.2	99.4
2 F	103.2	98.5	12 F	104.4	99.6
2 H	103.4	98.7	12 H	104.9	100.1
2 J	103.5	98.8	12 J	104.8	100.0
2 L	103.6	98.9	12 L	105.1	100.3
3 A	---	---	11 A	---	---
3 C	---	---	11 C	---	---
3 E	[1]99.7	95.0	11 E	[1]97.4	92.6
3 G	100.0	95.3	11 G	100.2	95.4
3 I	100.0	95.3	11 I	100.7	95.9
3 K	99.9	95.2	11 K	101.4	96.6
3 L	100.1	95.4	11 L	101.5	96.7
4 B	---	---	10 B	---	---
4 D	[1]95.55	90.85	10 D	[1]96.65	91.85
4 F	95.7	91.0	10 F	96.60	91.80
4 H	96.2	91.5	10 H	97.4	92.60
4 J	97.3	92.6	10 J	98.6	93.8
4 L	97.6	92.9	10 L	99.0	94.2
5 A	---	---	9 A	---	---
5 B	---	---	9 B	---	---
5 C	---	---	9 C	---	---
5 D	[1]121.6	116.9	9 D	[1]91.5	86.7
5 E	[1]89.9	85.2	9 E	[1]91.2	86.4
5 F	[1]89.95	85.25	9 F	[1]90.0	85.2
5 G	89.5	84.8	9 G	91.5	86.7
5 H	91.3	86.6	9 H	92.6	87.8
5 I	93.4	88.7	9 I	94.7	89.9
5 J	94.1	89.4	9 J	95.7	90.9
5 K	95.8	91.1	9 K	96.2	91.4
5 L	95.7	91.0	9 L	96.7	91.9
6 A	---	---	8 A	---	---
6 B	---	---	8 B	---	---
6 C	---	---	8 C	---	---
6 D	[1]87.25	82.55	8 D	[1]122.1	117.3
6 E	[1]87.0	82.3	8 E	[1]87.9	83.1
6 F	[1]85.8	81.1	8 F	[1]86.7	81.9
6 G	82.7	78.0	8 G	83.5	78.7
6 H	88.35	83.65	8 H	86.4	81.6
6 I	90.5	85.8	8 I	91.6	86.8
6 J	93.4	88.7	8 J	90.4	85.6
6 K	94.8	90.1	8 K	93.5	88.7
6 L	94.9	90.2	8 L	95.4	90.6

Position	Total head of water	Manometer reading	Position	Total head of water	Manometer reading
	-----Centimeters-----				
7 A	---	---			
7 B	---	---			
7 C	---	---			
7 E	[1]87.5	82.8			
7 F	[1]60.2	55.5			
7 H	89.1	84.4			
7 H'	88.9	84.2			
7 I	---	---			
7 I'	90.9	85.3			
7 K	94.7	90.9			
Drain	[3]71.6	66.9			

[1] Discarded data due to tension at the piezometer location.
[2] Maximum potential.
[3] Minimum potential.

Drain diameter:	4.5 inches	Time:	11:00 a.m.
Outflow:	2.722 L/min	Date:	March 2, 1973
State:	Steady, free water table	Temperature:	19.8°C
Drain type:	PVC, corrugated fiber glass	Reader:	Akin Orhun

Position	Total head	Pressure of H_2O	Position	Total head	Pressure of H_2O
	Percent	*Centimeters*		*Percent*	*Centimeters*
1 A	---	---	13 A	---	---
1 B	---	---	13 B	---	---
1 C	---	---	13 C	---	---
1 D	[1]92.09	-16.52	13 D	[1]94.82	-15.52
1 E	95.64	.02	13 E	97.27	.62
1 F	95.91	15.36	13 F	---	---
1 G	96.73	30.90	13 G	99.18	31.80
1 H	95.36	45.64	13 H	99.45	47.14
1 I	96.73	61.38	13 I	100.00	62.58
1 J	97.27	76.82	13 J	99.18	77.52
1 K	96.45	91.76	13 K	92.54	92.16
1 L	---	---	13 L	97.82	102.42
2 B	---	---	12 B	---	---
2 D	[1]86.37	-18.62	12 D	[1]88.82	-17.72
2 F	86.10	11.76	12 F	89.37	12.96
2 H	86.64	42.44	12 H	90.73	43.94
2 J	86.92	73.02	12 J	90.46	74.32
2 L	87.19	98.52	12 L	91.28	100.02
3 A	---	---	11 A	---	---
3 C	---	---	11 C	---	---
3 E	[1]76.56	-6.98	11 E	[1]70.19	-9.28

Position	Total head	Pressure of H_2O	Position	Total head	Pressure of H_2O
	Percent	*Centimeters*		*Percent*	*Centimeters*
3 G	77.38	23.80	11 G	77.92	24.00
3 I	77.38	54.28	11 I	79.29	54.98
3 K	77.11	83.96	11 K	81.19	86.16
3 L	77.65	95.02	11 L	81.47	96.42
4 B	---	---	10 B	---	---
4 D	[1]65.25	-26.37	10 D	[1]68.25	-25.27
4 F	65.66	4.26	10 F	68.11	5.16
4 H	67.02	35.24	10 H	70.29	36.44
4 J	70.02	66.82	10 J	73.56	68.12
4 L	70.84	92.52	10 L	74.65	93.92
5 A	---	---	9 A	---	---
5 B	---	---	9 B	---	---
5 C	---	---	9 C	---	---
5 D	[1]136.23	-.32	9 D	[1]54.22	-30.42
5 E	[1]49.86	-16.78	9 E	[1]53.40	-15.48
5 F	[1]50.00	-1.49	9 F	[1]50.13	-1.44
5 G	48.77	13.30	9 G	54.22	15.30
5 H	53.67	30.34	9 H	57.22	31.64
5 I	59.40	47.68	9 I	62.94	48.98
5 J	61.30	63.62	9 J	65.66	65.22
5 K	65.94	80.56	9 K	67.02	80.96
5 L	65.66	90.62	9 L	68.39	91.62
6 A	---	---	8 A	---	---
6 B	---	---	8 B	---	---
6 C	---	---	8 C	---	---
6 D	[1]42.64	-34.67	8 D	[1]137.60	.18
6 E	[1]41.96	-19.68	8 E	[1]44.41	-18.78
6 F	[1]38.69	-5.64	8 F	[1]41.14	-4.74
6 G	30.24	6.50	8 G	32.42	7.30
6 H	45.64	27.39	8 H	40.32	25.44
6 I	51.49	44.78	8 I	54.49	45.88
6 J	59.40	62.92	8 J	51.22	59.92
6 K	63.21	79.56	8 K	59.67	78.26
6 L	63.48	89.82	8 L	64.85	90.32
7 A	---	---			
7 B	---	---			
7 C	---	---			
7 E	[1]43.32	-19.18			
7 F	[1]-31.06	-31.24			
7 H	47.68	28.14			
7 H'	47.13	31.75			
7 I	---	---			
7 I'	50.13	36.66			
7 K	62.94	79.46			

[1]Discarded data due to tension at the piezometer location.

Comments: Water-table elevations are as follows:

Column	Water table (cm)	Column	Water table (cm)
1	106.8	7	---
2	103.2	8	83.5
3	100.0	9	91.5
4	95.7	10	96.6
5	89.5	11	100.2
6	82.7	12	104.4
		13	107.3

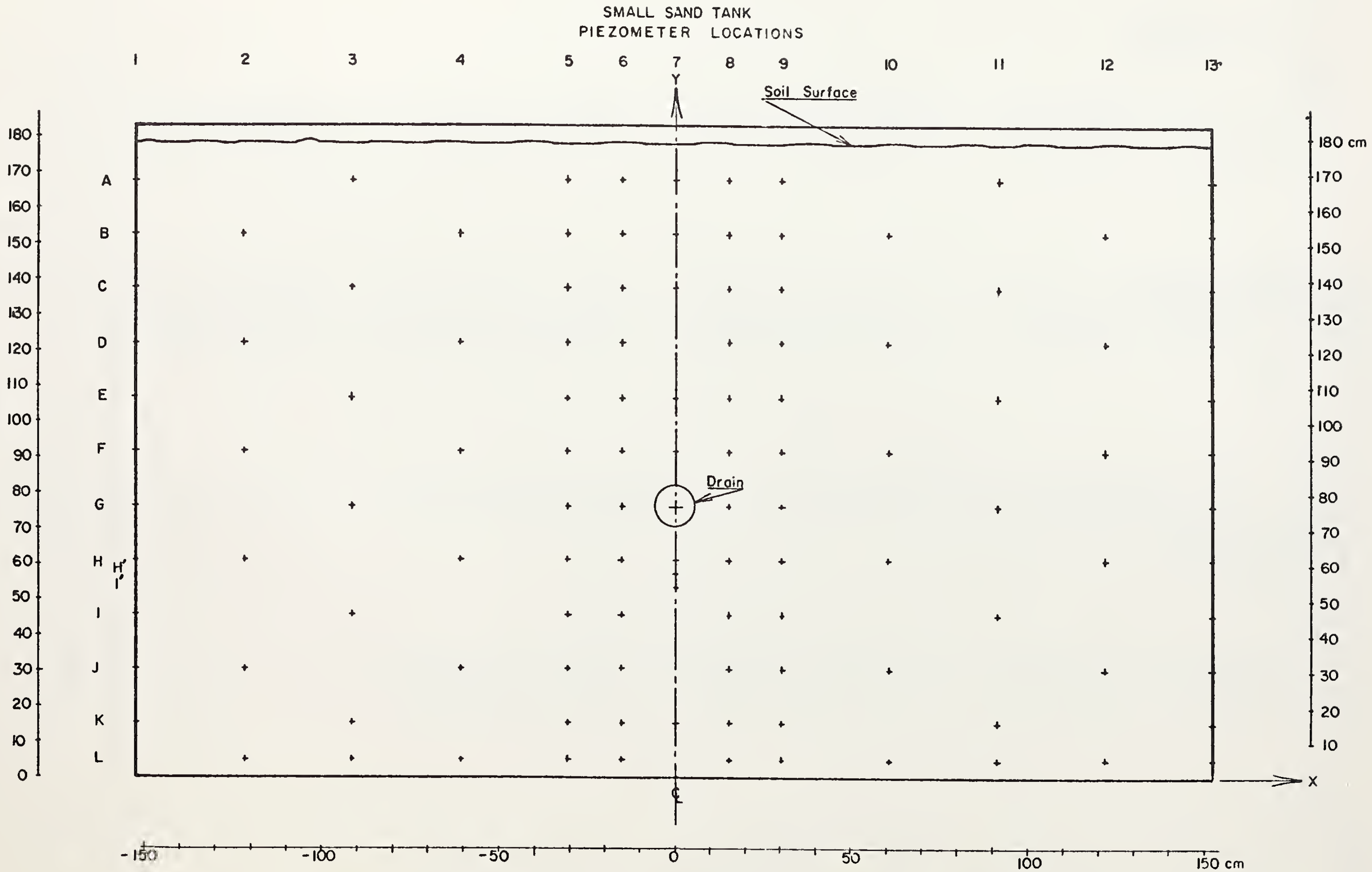
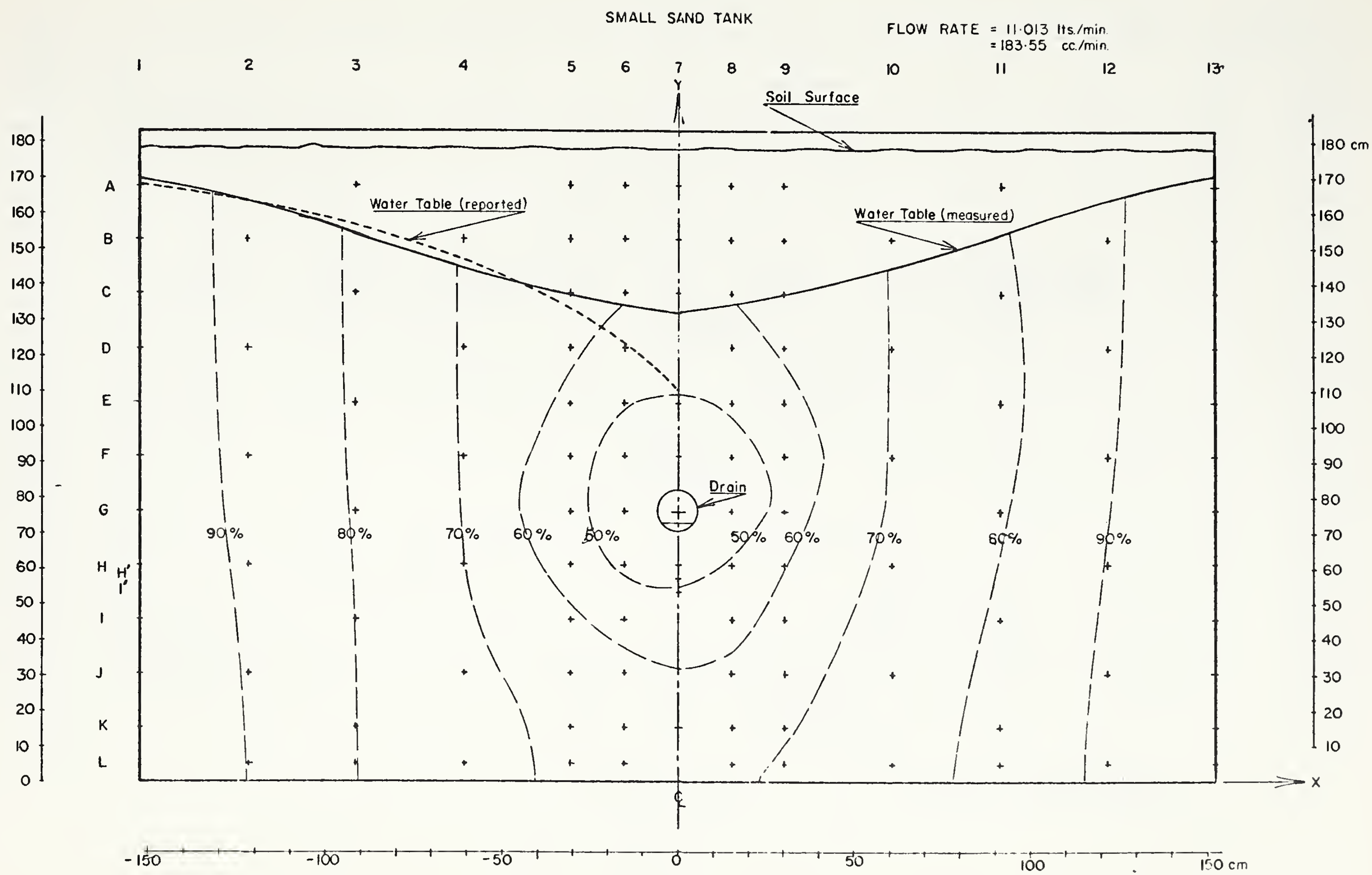


Figure 1.--Locations and general arrangement of piezometers.



SMALL SAND TANK
FLOW RATE = 11·013 lts./min.
= 183·55 cc./min.
Soil Surface
Water Table (reported)
Water Table (measured)
Drain
90%
80%
70%
60%
50%
180 cm
150 cm

Figure 2.

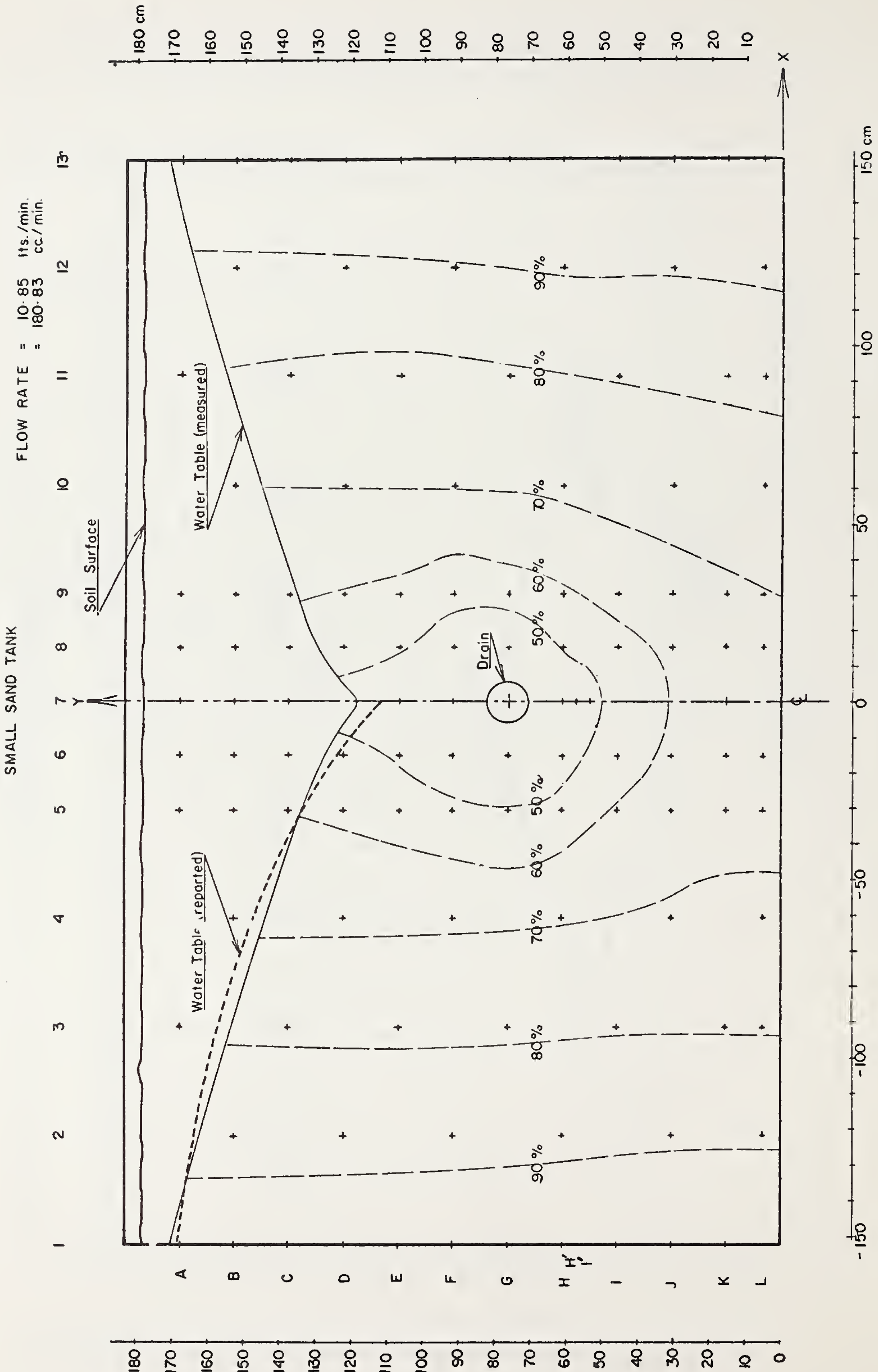
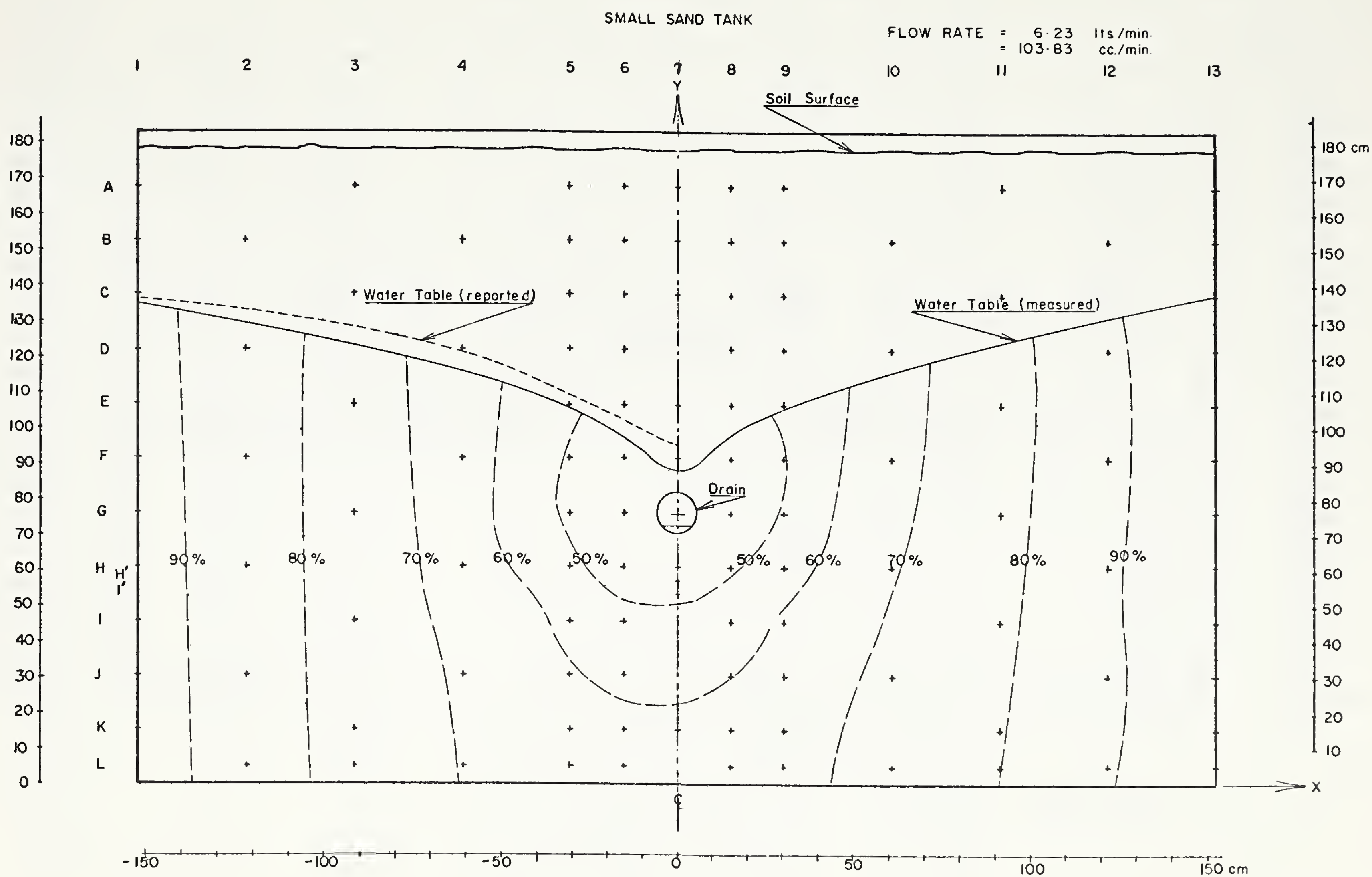

SMALL SAND TANK
FLOW RATE = 10·85 lts./min.
= 180·83 cc./min.
Soil Surface
Water Table (measured)
Water Table (reported)
Drain
90%
80%
70%
60%
50%
180 cm
150 cm
100
50
0
-50
-100
-150
A
B
C
D
E
F
G
H
I
J
K
L
1
2
3
4
5
6
7
8
9
10
11
12
13
X
Y

Figure 3.



SMALL SAND TANK
FLOW RATE = 6·23 lts/min.
= 103·83 cc./min.
Soil Surface
Water Table (reported)
Water Table (measured)
Drain
90%
80%
70%
60%
50%
A
B
C
D
E
F
G
H
H'
I'
I
J
K
L
1
2
3
4
5
6
7
8
9
10
11
12
13
Y
X
180 cm
150 cm

Figure 4.

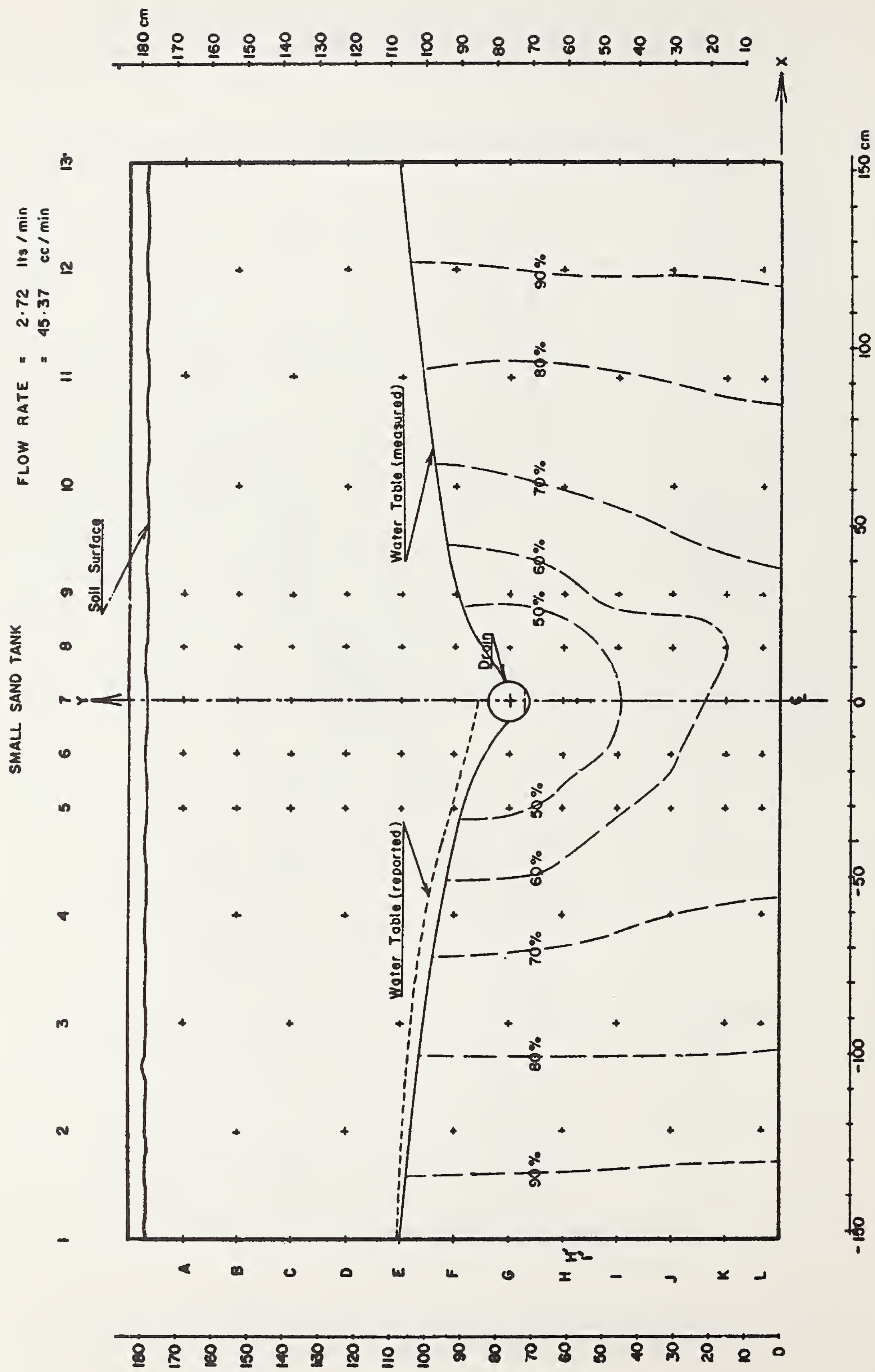

SMALL SAND TANK
FLOW RATE = 2·72 lts / min
= 45·37 cc / min
Soil Surface
Water Table (measured)
Water Table (reported)
Drain
90%
80%
70%
60%
50%
180 cm
150 cm

Figure 5.

HYDRAULIC GRADIENTS IN ENVELOPE MATERIALS

By L. S. Willardson[1]

Hydraulic conductivity and hydraulic gradients in drain envelope materials were measured in the laboratory with permeameters 5.1 cm in diameter and 20.3 cm long. Piezometer taps were located around the wall of the permeameter at four circumferential positions, 90° apart. The longitudinal spacing was 3.8 cm. Tests were made for a range of hydraulic gradients for each material.

The envelope material used was typical for drains in the Imperial Valley of California. The gradient curve is shown in figure 1. The material is well graded and functions satisfactorily as a drain envelope in all Imperial Valley soil types. A large sample of the envelope material was screened into size-range separates for detailed conductivity and gradient tests.

Hydraulic conductivity is usually stated as a single value for porous materials. Determinations of hydraulic conductivity are normally made at a hydraulic gradient of 1.0 or less. Luthin et al.[2] found that very high gradients can develop adjacent to drain openings. Hydraulic gradients greater than 1.0 in coarse materials can result in non-Darcy flow and high inertial energy losses in addition to the viscous energy loss at drain openings. The circles in figure 1 indicate the hydraulic conductivity of the reference envelope material (about the same as that of the smallest separate) as well as the indicated size separates at a gradient of 1.0.

Figure 2 shows the variation in hydraulic conductivity of the different sizes of materials with different hydraulic gradients. The variations were greatest for particle sizes above 2.0 mm. The low values of hydraulic conductivity at the beginning low gradients are attributed to entrapped air in the samples. Air was removed from the water used for the tests.

These permeameter tests suggest that for graded materials or for finer (<2.0 mm) single-size envelope materials, hydraulic gradients up to 10.0, do not result in appreciably greater head losses, that is, lower apparent hydraulic conductivities at higher gradients.

---

[1] Professor, Department of Agricultural and Irrigation Engineering, Utah State University, Logan.

[2] Luthin, J. N., G. S. Taylor, and C. Prieto. Exit gradients into subsurface drains. Hilgardia 39(15): 419-428.

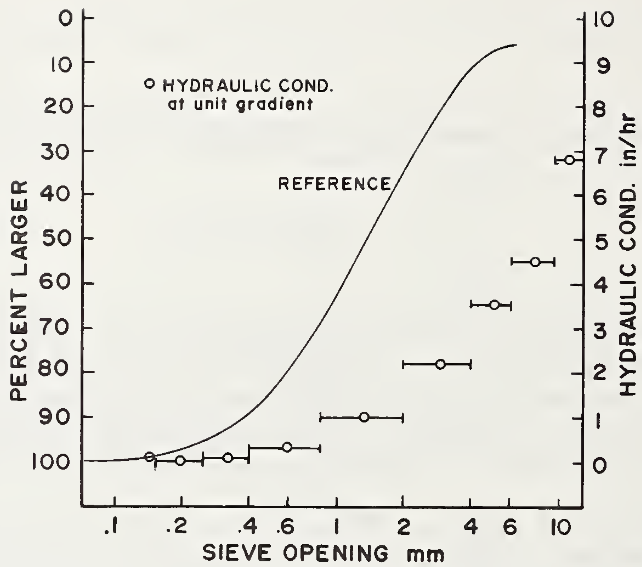


Figure 1.--Grading curve and hydraulic conductivities for Imperial Valley drain envelope materials.

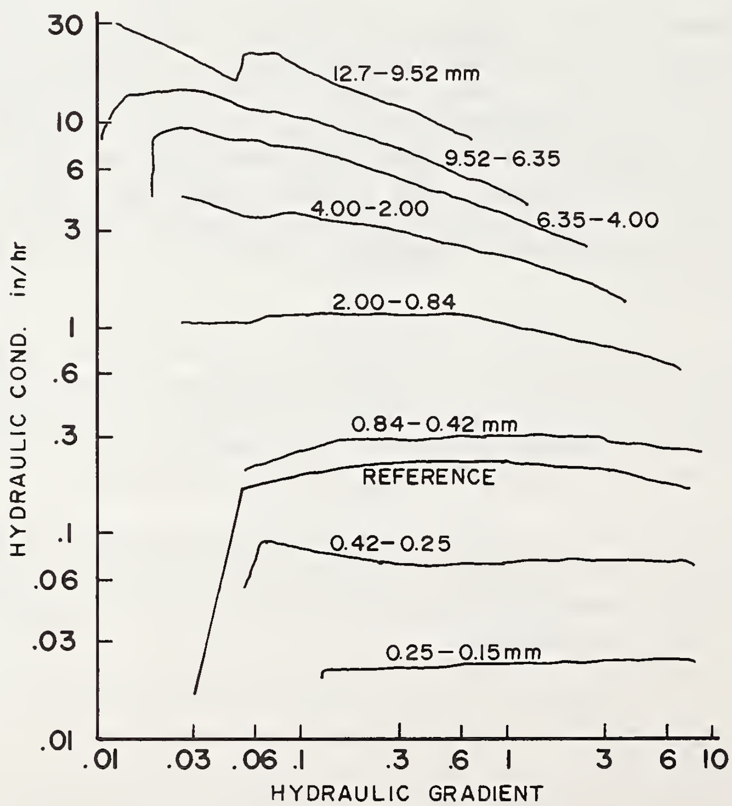


Figure 2.--Variation of hydraulic conductivity with gradient for sized materials.

Envelope Effects on Head Loss at Drain Openings

The opening into a drain is a form of orifice. In free water, an orifice discharge coefficient can be obtained for any shape of opening to predict head loss at any flow. Flow conditions are drastically altered, however, when granular material is placed next to a drain opening. No single coefficient describes the head loss. It is possible, for example, for the opening into a drain to be completely plugged by a single particle slightly larger than the opening. In this case, the discharge coefficient would be zero. To prevent such an occurrence, it is desirable to have drain openings larger than the majority of particles in the envelope material. The drain openings should not be so large (relative to the envelope particles) that the particles will flow through and not bridge over the opening.

To determine the magnitude of head losses caused by placement of envelope materials next to orifices, the permeameter was used with an orifice plate added in the bottom. The orifice plate had piezometer taps 0.38, 0.76, and 1.52 cm from the center of the plate on four radii.

Four orifice-plate opening sizes were used with three sizes of envelope material. In addition, the head losses at the orifices were determined without envelope material. The reference envelope material was tested with the largest orifice.

When a test had been completed on flow-through material that was initially placed dry in the permeameter, a wire was placed in the orifice opening while water was kept flowing to disturb the material. The amount of material that passed the opening (after the disturbance) was determined, and the flow test was repeated.

The head difference chosen for comparison of discharge was that measured between the submerged outlet side of the orifice and the piezometric pressure measured 0.38 cm from the center of the orifice.

Table 1 shows the flow rates obtained with a 102-cm head difference across the orifices for three test conditions. It includes the flow rates for the open orifices and for the orifices before and after disturbance of the material. As expected, placement of the envelope material at the orifice reduced the discharge. The percentage reduction was variable, depending on the random arrangement of the particles at the opening. The maximum reduction was 77 percent for the 2.64-mm orifice and the 0.84-2.00-mm material. The minimum reduction was only 13 percent. Reductions in flow tended to be smallest for the smaller orifices and the larger material. The reductions were greatest where the particles were almost the same size as the orifices. Disturbing the material at the opening increased the discharge, that is, reduced the head loss in all cases except for the pit-run material. A single large particle in the pit-run material partially blocked the orifice.

Larger material did not pass through orifices which were disturbed with a wire during flow. The greatest amount of material passed was from the smallest size tested with the largest opening. Table 2 shows the weights of material passing the orifices after mechanical disturbance. Test number 1077 had the smallest amount of material movement but the greatest percentage increase in flow

following disturbance. Effective bridging occurrred in all tests, and flow improved after disturbance, but the amount of material passed in test 1125 was excessive.

Bridging at Drain Openings

Placement of envelope material around drains is done with dry material that will flow readily into place, falling in a random arrangement at the drain openings. The envelope material usually contains a gradation of sizes, and some of the smaller ones naturally fall through the openings. Once the material is me-

TABLE 1.--*Flow rates with 102 cm of head difference before and after disturbance of envelope material at the orifice*

Orifice diameter	Flow rate								
	Empty	Particle sizes in millimeters							
		0.84-0.42		2.00-0.84		4.00-2.00		Pit run	
		Before	After	Before	After	Before	After	Before	After
	Cm^3/sec								
1.59	7.7	2.9	4.3	1.8	---	6.7	7.3	---	---
2.18	13.6	7.3	10.0	3.6	5.2	7.1	11.0	---	---
2.64	20.5	10.3	10.6	4.8	16.3	7.0	9.5	---	---
3.05	29.1	13.4	14.9	16.7	19.4	12.7	14.0	23.0	10.2
Average	17.72	8.48	9.95	2.28	10.22	8.38	10.45		

TABLE 2.--*Weights of material washed through orifices after disturbance*

Test No.	Orifice diameter	Particle sizes	Weight passing
	Millimeters		*Grams*
1005	1.59	2.00-0.84	0
1022	1.59	0.84-0.42	0
1033	2.18	2.00-0.84	0
1049	2.18	0.84-0.42	1.800
1077	2.64	2.00-0.84	.098
1087	2.64	0.84-0.42	3.352
1115	3.05	2.00-0.84	.598
1125	3.05	0.84-0.42	21.166
1143	3.05	([1])	1.337

[1]Pit-run material sizes 2.00-0.074 mm passed the opening. Gradation of the passed material did not correspond to the original sample.

chanically stabilized by the placement of the trench backfill, there is little movement when the drain begins to function. Any movement of material after installation would require an outside energy source such as ground shocks or cleaning with a high-pressure water jet to disturb the material and cause additional movement into the drain.

Laboratory tests were conducted to evaluate the effectiveness of the bridging action of dry material at drain openings. Dry envelope material was poured onto simulated drain openings. A circular plate 5 cm in diameter was placed in the bottom of a permeameter 10 cm high. The material was poured from a height of 15 cm. The plate was 0.7 mm thick. Most of the tests for a range of material sizes were conducted with circular openings, although a rectangular slot of 3.2 by 32 mm was also tested. The envelope materials were six separates from the reference Imperial Valley envelope material. About 200 g of material was poured into the permeameter for each test. The tests were replicated three times.

Table 3 gives the weights of material passing each opening. As expected, for a given size of opening, more of the finer sizes passed through. When the openings were much larger than the material, the entire sample flowed through the opening. In table 3, the spaces marked ([2]) indicate complete passage of the envelope material. When the smallest particles in the separates were larger than the openings, no material was passed. For the middle range of sizes, bridging was effective after a few seconds, stopping further particle movement through the opening.

TABLE 3.--*Weights of envelope material passing an opening in a flat plate*

Material sizes	Opening diameter in millimeters					
	1.59	3.18	5.84	6.35	9.52	3.18 x 31.75[1]
	Material weights					
	Grams					
0.25-0.149	8.354	([2])	([2])	([2])	([2])	([2])
0.42-0.25	.075	([2])	([2])	([2])	([2])	([2])
0.84-0.42	.031	2.000	([2])	([2])	([2])	([2])
2.00-0.84	0	.147	.881	3.727	([2])	8.143
4.00-2.00	0	.011	.060	.344	1.807	1.401
6.35-4.00	0	0	0	0	1.390	0
9.52-0.149[3]	.008	.071	.443	.764	9.275	1.543

[1]Oblong slot.
[2]All material passed through opening.
[3]Reconstructed composite sample of pit-run material.

After bridging had occurred, the bridged material was disturbed with a wire. The amount of material that passed the opening after artificial disturbance was about the same as that passed originally. The pit-run material bridged all the

openings tested.

In addition to the circular openings, a slot approximating the opening used in plastic drain tubing was tested. The effective size of the slot for bridging purposes was the same as that of a circular opening, with a diameter three times the narrow dimension of the slot.

Table 4 shows the sizes of particles that would not bridge openings. Spaces in the table to the right of the numbers indicate opening sizes that passed all of the materials without bridging. The numbers in the table indicate the size of the opening relative to the particles passing.

TABLE 4.--*Opening diameters divided by diameters of particles that flowed through openings without bridging*

Material sizes (millimeters)	Opening diameter in millimeters					
	1.59	3.18	5.84	6.35	9.52	3.2 x 32.0
	------------*Ratio of opening diameter to particle size*-----------					
0.25-0.149	(1)	2.72-21.34				
0.42-0.25	(1)	7.57-12.72				
2.00-0.84	(1)	(1)	6.95-13.90			
4.00-2.00	(1)	(1)	(1)	(1)	4.76-11.33	
6.35-4.00	(1)	(1)	(1)	(1)	(1)	(1)
9.52-0.149	(1)	(1)	(1)	(1)	(1)	(1)

[1]Bridging of particles.

In table 4, the spaces marked (1) indicate material and opening sizes at which bridging occurred to some degree. Table 4 shows that bridging will occur for a narrow range of material gradings if the particles are one-third the size of a circular opening or larger.

About 2.37 g of granular material will just fill the bottom of one corrugation of a typical corrugated plastic drain tube 4 inches in diameter. The data from the pit-run sample in table 3 indicate that a single opening about 7 mm in diameter would allow this amount of material to enter the drain. The slot having a minimum dimension of 3.18 mm provided adequate protection from excessive passage of envelope material before bridging occurred.

Placement of envelope material adjacent to drains will improve the overall hydraulic performance of the drain. The envelope material will bridge drain openings if the particles are larger than one-third the diameter of an equivalent circular opening. A slot has the same effective size as a circular hole with a diameter three times the narrow dimensions of the slot. Coarse materials adjacent to drain openings may develop non-Darcy flow at gradients greater than 1.0.

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